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APPLICATION NOTE

AP-73

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ECC #2
Memory System Reliability with ECC

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01305A

1. INTRODUCTION

This Application Note explains reliability analysis as applied to a typical memory system. (It follows Intel Application Note AP-46, which reviewed basic ECC, **Error Corrections Code,** concepts.) A number of examples demonstrate techniques to calculate reliability of a model memory system, with and without ECC — emphasizing system reliability as a function of the number of devices in a system and the individual device failure rates.

Since a system with ECC can correct a single bit failure and detect double bit errors within an accessed word, it has a decided advantage over a system without ECC. A soft error rate of two or three times device hard failure rate has significantly less effect on the Mean Time Between Failures (MTBF) for a system with error correction. This is quantified as the Enhancement Factor, EF — the ratio of MTBF for two identical systems, one with and one without ECC. The Enhancement Factor can be predicted by the application of statistical analysis.

The general model presented in this Application Note numerically predicts the chance of memory system failures during a specified length of time. It also provides insights into the relationship of device failure mechanisms and soft errors to memory system reliability. Intel® 2117 Dynamic RAM is used in the example memory system. The reliability data for distribution of hard failures was obtained from the 2117 Reliability Report (Intel RR-20).

2. MEMORY CONFIGURATION

2.1 Device

System reliability begins with the smallest physical unit, the memory device. Each device can be considered a system itself, with the smallest functional unit being a single storage cell. Device internal structures have inherent failure mechanisms affecting individual memory cells.

The structure of a typical RAM device consists of two-dimensional coordinate-addressed arrays of memory cells arranged in rows and columns, such as the Intel® 2117 Dynamic RAM shown in Figure 2. This device contains 16384 cells arranged in a 128 row by 128 column matrix; each cell is selected by an encoded 7-bit row and 7-bit column address.

2.2 System

An array of memory devices on one or more circuit boards forms a typical memory system. A system is defined by n bits per word, x words per page and p pages per system. Note that a "page" is defined as the number of memory words formed by a minimum set of memory components.

For example, 16K by 1 RAMs would have a minimum page size of 16384 words.

Figure 1 represents such a system, with the horizontal axis corresponding to parallel, address-accessed data bits and the vertical axis corresponding to the series stacking of words and pages. This memory structure is used for the model system.

3. ERROR CLASSIFICATION

The 2117 failure mechanisms illustrated in Figure 3 are fairly representative for today's RAM devices. These can be categorized as **hard failures** and **soft errors.**

3.1 Hard Failures

Hard failures are permanent physical defects, such as shorts, open leads, micro-cracks or other intrinsic flaws. They are classified as single cell failures, row failures, column failures, combined row-column failures, half-chip failures and full-chip failures.

The failure type distribution within a device is a function of the device design. Typical ratios are 50% single cell failures, 40% row or column failures, 10% combined failures and less than 0.1% half-chip or full-chip failures. (Refer to Figure 4.) The accumulative independent events are expressed as a single numeric value for the combined failure rate of the device (EQ:1a). The standard mathematical symbol for device failure rate is the Greek letter Lambda, λ; i.e., $\lambda = 0.027\%/1000$ hrs.

EQ:1a $$\lambda_{hrd} = \lambda_{single} + \lambda_{row} + \lambda_{column} + \lambda_{row/col} + \lambda_{halfchip} + \lambda_{fullchip}$$

3.2 Soft Errors

In contrast to hard failures, soft errors are characterized as being random in nature, non-recurring, non-destructive single cell errors.

Traditional soft errors are caused by noisy system environments, poor system design, or rare combinations of noise, data patterns, and temperature effects which push the RAM beyond its normal specified range of operation. This type of soft error has not been included in the analysis to follow because it is associated with system level problems and the rate of failure is difficult to quantify; in any case it is assumed to be quite small.

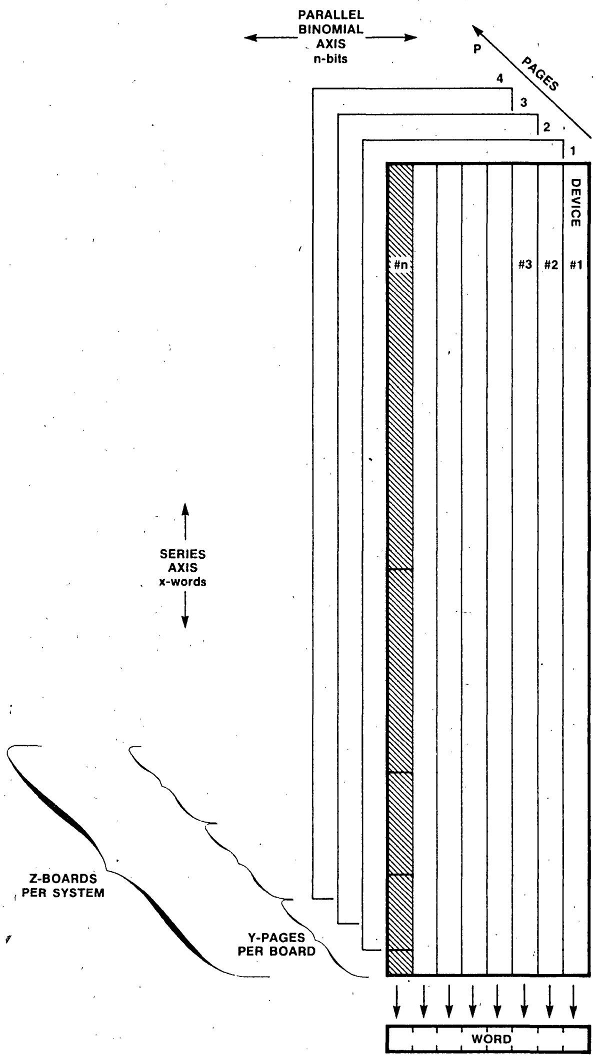


Figure 1. Memory Configuration

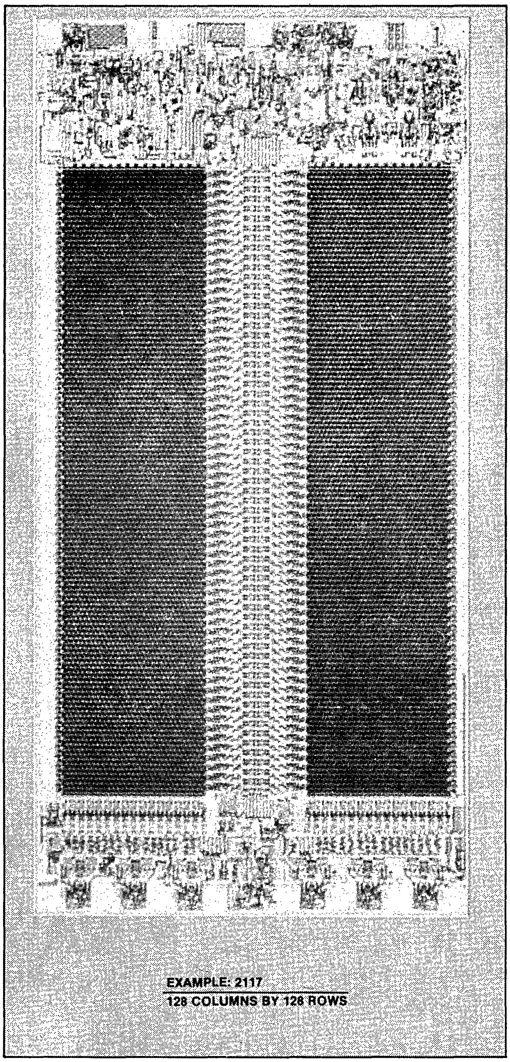


Figure 2. Random Access Memory Device

Other soft errors are caused by ionizing radiation of alpha particles changing memory cell charge in semiconductor substrates with high impedance nodes. The data bit error is realized during a memory read to the failing cell. These errors are purged by rewriting (restoring) the correct data bit information to the cell. The failure rate for this type of soft error is stated separately from hard failures because of its unique properties.

The total device failure rate becomes:

EQ:1b $\lambda_{dev} = \lambda_{hrd} + \lambda_{sft}$

The pie graph in Figure 5 depicts the combined distribution of both hard and soft errors.

4. RELIABILITY

Reliability, as used in this application note, is defined as "the probability that a component will operate within specified limits, for a given period of time"[1]. The definition includes the term "probability", a quantitative measure for chance or likelihood of occurrence, of a particular form of event — in this case, operation without failure within specified limits. In addition to the probabilistic aspect, the reliability definition also involves length of operational time.

Since reliability is concerned with events which occur in the time domain, they are classified as incidental failures, which do not cluster around any mean life period, but occur at random time intervals. The exact time of failure cannot be predicted; however, the probability of occurrence or non-occurrence of a statistical mean in a given operating frame of time can be analyzed by the theories of probability. Since exact formulae exist for predicting the frequency of occurrence of events following various statistical distributions, the chance or probability of specified events can be derived.

4.1 Component Reliability

Memory systems are operated where failures occur randomly due only to chance causes. The fundamental principles of reliability engineering predict the failure rate of a group of devices which will follow the so-called bathtub curve in Figure 6. The curve is divided into three regions: Infant Mortality, Random Failures, and Wearout Failures. All classes of failure mechanisms can be assigned to these regions.

Infant Mortality, as the name implies, represents the early life failures of a device. These failures are usually associated with one or more manufacturing defects. Memory device failures occurring as the result of Infant Mortality have been eliminated by corrective actions relating design, inspection, and test methods.

Wearout failures occur at the end of the device's useful life and are characterized by a rising failure rate with time as the device's "wearout" both physically and electrically. This does not occur for hundreds of years for integrated circuits.

The Random Failure portion of the curve represents the useful period of device life. As stated, memory devices are operated in systems during this period when failures occur randomly. The number of failures occurring during any time interval within the "Random" period is related only to the total number of memory components

[1] *Reliability Mathematics* — Amstadter

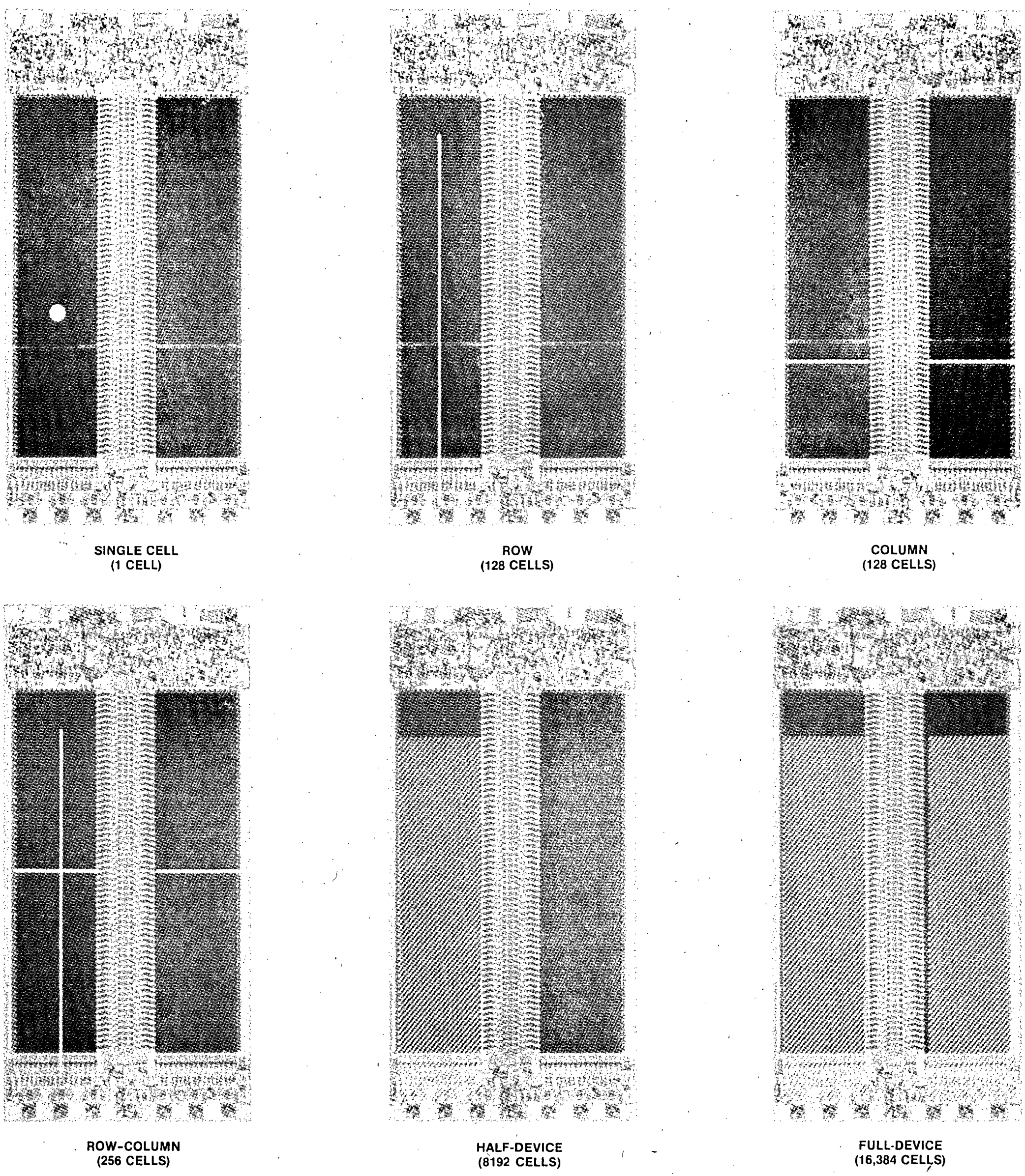


Figure 3. Failure Geometry — 2117 Example

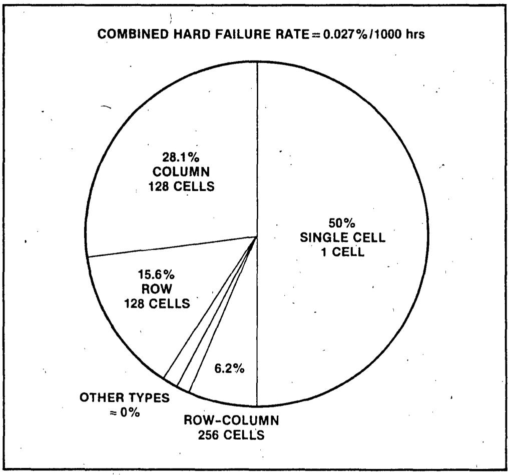


Figure 4. Failure Distribution — 2117 Example

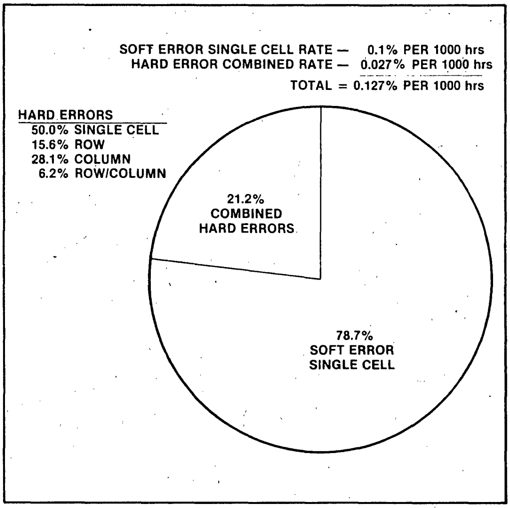


Figure 5. Combined Distribution of Failure Type

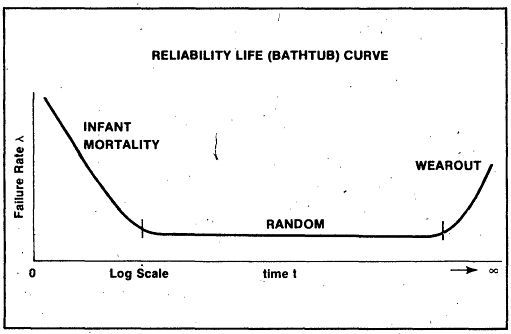


Figure 6. Reliability Life Curve

operating. If sufficient numbers are operated, and the measured interval is long enough, failure rate approaches some relative constant value. For any given component type, the failure rate value will depend on operating and external environmental conditions (voltage, temperature, timing, etc.) and will be characteristic of this set of conditions. When the conditions change, the failure rate will correspondingly change.

For example, if 500 devices are tested for 1,500 hours and two failures were observed during the test interval, then the failure rate is two failures per 750,000 device-hours or one failure per 375,000 device-hours. For commonality, device failure rates are expressed as a percentage value per 1000 device-hours. The above example then becomes .00266 failures per 1000 device-hours or $\lambda_{dev} = 0.27\%$ per 1000 hours. This is an overly simplified statement on determining the device failure rate. Many tests, designed to stress the devices over operating conditions and margins, are used in the final analysis for the specification of device failure rates.

4.1.1 RELIABILITY FUNCTION R(t)

The Reliability Function, R(t), follows an inverse, natural logarithmic curve, which expresses the rate of change for a memory component from an operational state to a failure or error condition. The curve is a familiar one to the physical scientists because of its relationship to growth and decay.

The general function for reliability is given in EQ:2 where the exponent $(\lambda \cdot t)$ represents the device failure "lambda" times the independent time variable "t". The graph in Figure 7 shows the shape of the R-function curve.

EQ:2 $R(t) = e^{-\lambda t}$

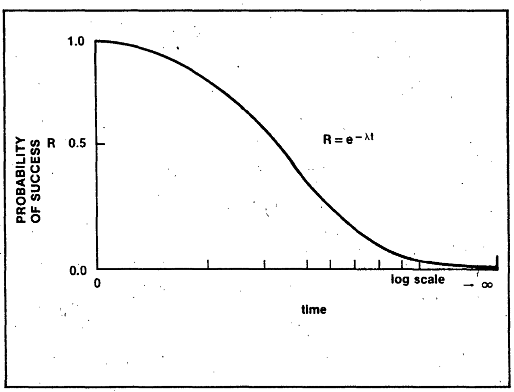


Figure 7. R(t) - Reliability Function

For any constant failure rate the value of reliability depends only on time. The limits of the reliability function R(t) are:

$$R(0) = 1.0 \text{ and } R(\infty) = 0.0$$

The distribution is a one-parameter type; in that once the failure rate is established, the reliability function is completely defined. For high or low failure rates the general shape of the curve remains the same, but is adjusted along the time axis.

4.2 System Reliability

Just as there is a functional relationship between the components and the system, there is a functional relationship between component reliability and system reliability. If a failure in any one of the components of a system causes the entire system to fail, the system is a "Series System" (Figure 8).

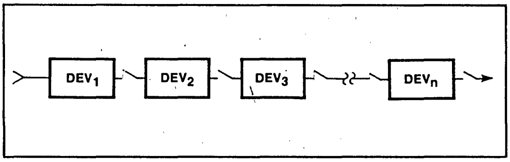


Figure 8. System of Series Components

If all the component devices must fail before the system fails, the system is a "Parallel System" (Figure 9).

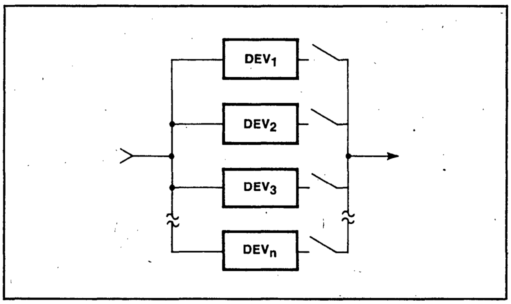


Figure 9. Parallel System

If a system has 'n' components which operate in parallel, but 'j' out of the 'n' components need to be functional for the system to operate, then this system is referred to as a "Parallel Binomial System" (Figure 10).

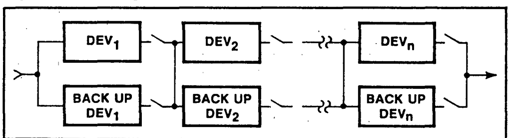


Figure 10. Parallel Binomial System

4.2.1 EQUATION FOR A SERIES SYSTEM

The Reliability Function for a series system is the product of the reliabilities of the individual components. If "n" components with corresponding failure rate of $\lambda_1, \lambda_2, \lambda_3, , , , \lambda_\eta$ operate in series to form a system then the equation for system reliability is:

EQ:3 $$R(t)_{sys} = R(t)_1 \cdot R(t)_2 \cdot R(t)_3 \cdot , , , R(t)_\eta \quad \text{where } R(t)_i = e^{-\lambda_i \cdot t}$$

If each of the n components has the same device failure rate lambda, then the system reliability equation reduces to:

EQ:4 $$R(t)_{sys} = R(t)^\eta = e^{-\eta\lambda t}$$

4.2.2 EQUATION FOR A PARALLEL BINOMIAL SYSTEM

One of the fundamental concepts of reliability engineering is the Binomial Theorem. The theorem is used for computing the reliability of complex redundant systems, where "j" out of "n" units are required to operate for system success. The binomial distribution expresses the probabilities of two states of an event, "a" and "b", where the event is permutated "n" ways. The general form of the binomial distribution is $(a + b)^\eta$, and is expanded to:

EQ:5 $$a^\eta + \eta a^{\eta-1} \cdot b + \frac{\eta(\eta-1)a^{\eta-2} \cdot b^2}{2!} + \frac{\eta(\eta-1)(\eta-2)a^{\eta-3} \cdot b^3}{3!} + \cdots + b^\eta$$

It is applicable to a memory system operating in parallel; i.e., when there are only two possible states or results of an event — when a component of the system either conforms to requirements or is discrepant.

If we assign to one state the function of reliability — R(t), then the other state is Q(t), the function of non-reliability, which is the probability of being inoperative.

Recall that R(t) is a unity function, which ranges from 1.0 to 0.0, as a function of time. Since the sum of R(t) and Q(t) make up the whole "event", then EQ:6 defines Q(t). This relationship is also illustrated in Figure 11.

EQ:6 $$R(t) + Q(t) = 1 \text{ , then } Q(t) = 1 - R(t)$$

By substituting R(t) and Q(t) respectively for a and b, where R(t) is the probability of a device being good, Q(t) is the probability of the same device being defective, and "n" the number of units in parallel, then:

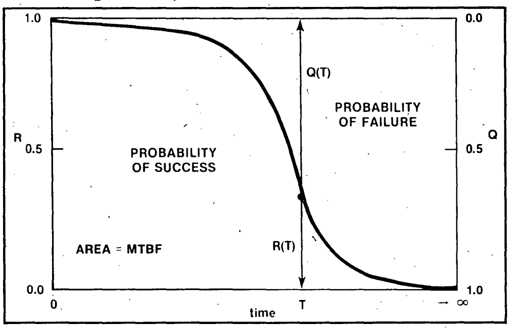


Figure 11. $Q(t) = 1 - e^{-\lambda t}$

EQ:7 $[R + Q]^{\eta} = 1$

Note, for simplicity, all references to (t) for the reliability and non-reliability functions will not be indicated, but implied.

It follows that the expansion of $[R + Q]^{\eta}$ must also equal unity example

EQ:8 $$R^{\eta} + \eta R^{\eta-1} \cdot Q + \frac{\eta(\eta-1)R^{\eta-2} \cdot Q^2}{2!} + \frac{\eta(\eta-1)(\eta-2)R^{\eta-3} \cdot Q^3}{3!} + \cdots + Q^{\eta} = 1$$

We can next examine the meaning of each term in the series on the left side of EQ:8. Suppose that there are "n" identical components of a system, of which the probability of a component being operative is R, and that the probability of its being inoperative is Q or $(1 - R)$. If there is only one component $(n = 1)$, then the probability of its being not defective is simply R.

If there are two components $(n = 2)$, then the probability of both being operative is $R \times R = R^2$; and if there were three components, then the probability of all three being good is R^3. Consequently, if there are "n" components, the chance of all "n" units being operative is R^{η} and the first term in the series R^{η} is the probability of all components being operational.

Next, suppose there are two components X and Y, one is operative and one has failed. There are two ways that this can occur: X is operational and Y fails, with the probability $R_x \cdot Q_y$; or X fails and Y is operational, with the probability $Q_x \cdot R_y$. Since these are mutually exclusive and constitute all possible combinations of one operative component and one failure, the total probability is $(R_xQ_y) + (Q_xR_y)$, or 2RQ.

If there are three components X, Y, and Z, of which two are operative and one fails, then three possible combinations exist: X and Y are operational and Z fails, X and Z operational and Y fails, and Y and Z operational and X fails. The probability of each combination is $(R_xR_yQ_z) + (R_xQ_yR_z) + (Q_xR_yR_z)$.

Again, since each combination is mutually exclusive and together they constitute all possible combinations, the probability of two operational devices and one failure is $3R^2 \cdot Q$. Similarly, if there are n component-devices, the probability of all but one being operative is $nR^{\eta-1} \cdot Q$. Thus, the second term of the binomial expansion series is the probability of exactly one device failure, and all other devices being good.

By extending these derivations to cover each succeeding term, we find that the third term is the probability of exactly two failed components, the fourth term is the probability of exactly three failures and so on. There are $n + 1$ terms in the expansion, and the last term Q is the probability all components are inoperative.

The reliability of a group of redundant items depends not only on the reliability of each individual item and on the number of items in redundant configuration, but also on how many are required to operate to achieve system success. If all are required, then the first term of the binomial series represents system success. In this case there is really no redundancy. However, if all but one are required (one failure permitted), then success is achieved if no failures occur or exactly one failure occurs within word accessed from a page of memory. The system reliability is then the sum of the first two terms of the series.

If two failures are permitted, then the sum of the first three terms represents the probability of system success. In general, if r failures are permitted, system success is the sum of the first $r + 1$ terms.

The general equation then for a binomial system, permitting one error, which is representative of a memory system with single bit error correction — ECC per accessed word is expressed as:

EQ:9 $$R_T(t) = \underbrace{R^{\eta}}_{\text{1st}} + \eta \cdot \underbrace{R^{\eta-1} \cdot Q}_{\text{2nd}} \quad \text{– binomial terms}$$

Note that the remaining terms of the binomial expansion represent all combinations of failures that are greater than one failure, up to and including all components failing. RT(t) is still a unity function of reliability and has a converse QT(t), where $QT(t) = 1 - RT(t)$. Thus, QT represents the 3rd through n-th terms of the binomial.

5. RELIABILITY ANALYSIS USING PAGE/SYSTEM APPROACH

The analysis of the model system in Figure 1 begins with EQ:2 at the smallest non-redundant failure level; by using standard rules for series and parallel reliability, the combination of these device exponential expressions will yield the system reliability equation. The method of approach will be to calculate the reliability of a page of memory and treat subsequent pages as a series system where:

EQ:10 $R(t)_{system} = [R(t)_{page}]^P$

For clarity, the reliability of power supplies, fans, backplane connections, TTL support logic, etc. will not be included. These items can be merged in the final analysis by the reader as additional series system equations for each type.

5.1 Memory System Without ECC

The analysis of reliability of a memory system "without" any form of ECC is simply the first term of the binomial equation EQ:9. Since this term represents reliability of all components in a page of memory without redundancy, it is equivalent to a "series system" equation (EQ:4). Therefore, the equation for a page of memory without ECC is:

EQ:11 $R(t)_{PAGE_{necc}} = R(t)^{\eta}_{DEV_{necc}} = e^{-\lambda \cdot n \cdot t}$

where "n" is the number of components in the page and λ_{dev} is the device combined failure rate.

The reliability for the memory system of "p" pages is:

EQ:12

$$R(t)_{SYS_{necc}} = [R(t)_{PAGE_{necc}}]^{p} = [R(t)_{DEV}]^{p \cdot \eta}$$

5.2 Memory System With ECC

The analysis of reliability of a memory system "with ECC" — (single bit error correction) is more complex. The fundamental difference between the two memory systems is that in a non-corrected system, any error — no matter the type, single cell failure, row failure, soft error, etc. — is considered a system failure. In a memory system with ECC, a system level failure only occurs when more than one bit has failed in an accessed word.

Thus in the analysis of a System with ECC, we must deal with the probabilities of each failure type occurring in random combinations which align within a word of memory to cause multiple bit failures as shown in Figure 12.

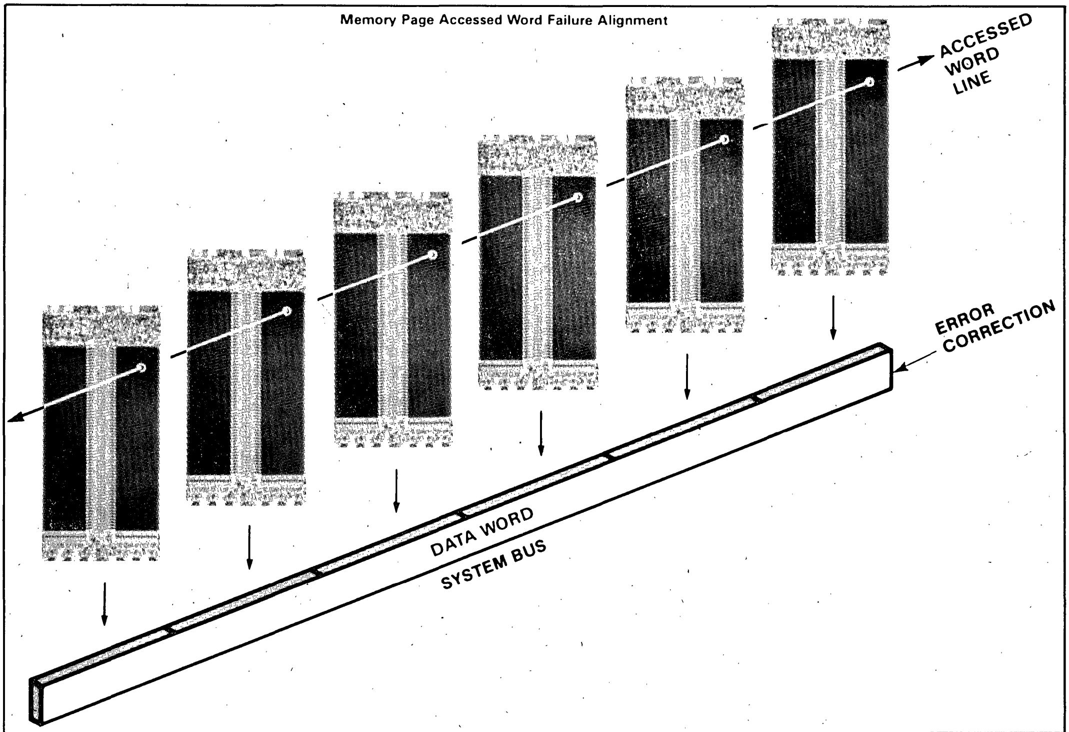


Figure 12. Memory Page Accessed Word Failure Alignment

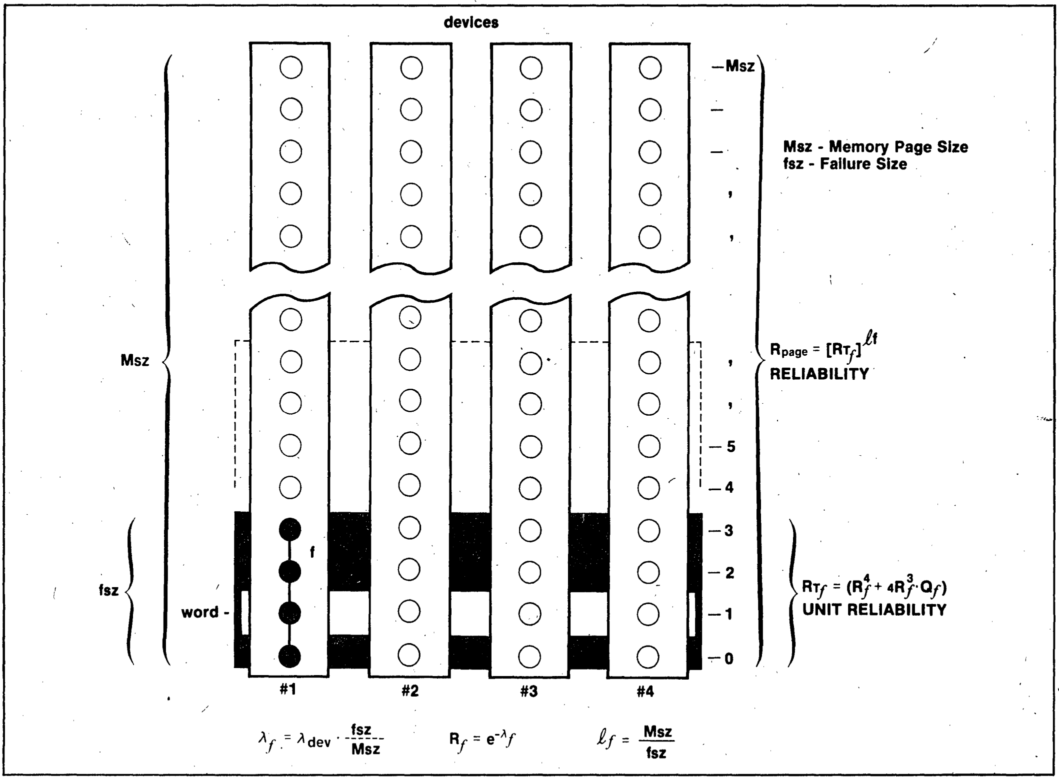


Figure 13. Single Failure Type Illustration

For example, consider a single cell hard failure in one device in a system using 16K RAMs. The chance of a similar failure in the same cell of a different device is 1/16384 times the device failure rate for single cells. For n devices in the data word the total chance is n/16384 for a single cell match.

The application of the binomial distribution (EQ:9) requires further differentiation in the analysis of the example memory system. EQ:9 is restricted to one failure mode, in that it typically assumes a failure renders the whole device inoperative. This is not the case with memory components where each device in itself can be thought of as a system of memory cells, with the smallest unit being the single cell.

Multiple devices have multiple failure modes, but usually when a failure occurs only a portion of the memory component is inoperative. Therefore, the application of EQ:9 must represent the **unit of failure** and be mutually inclusive with all other components along the accessed word (parallel axis) of the memory page.

The example in Figure 13 shows a four device memory array where each component has a single failure mechanism of type f, which affects fsz number cells during a failure. The unit failure rate λf is the ratio of {fsz/Msz} times the device failure rate λ_{dev}. Only that portion of the failure area, the shaded area in Figure 13, is mutually-inclusive with the failure when it occurs. Any additional failures outside the shaded area are mutually-exclusive, causing no double-bit failures in conjunction with "f."

The Reliability Function, RT, therefore, represents only a portion of the memory page as indicated by the shaded area fsz in Figure 13. If "f" were the only failure type, then the reliability for the full page is simply a series equation with RT raised to the exponent ℓ, the ratio Msz/fsz.

Derived from the binomial equation EQ:9, the expression for reliability for a single page of memory with one bit redundancy — (ECC) —, and only one failure type "x" is given as:

EQ:13

$$R(t)_{PAGEecc} = \left[R(t)_x^{\eta} + \eta \cdot R(t)_x^{\eta-1} \cdot Q(t)_x\right]^{\ell_x}$$

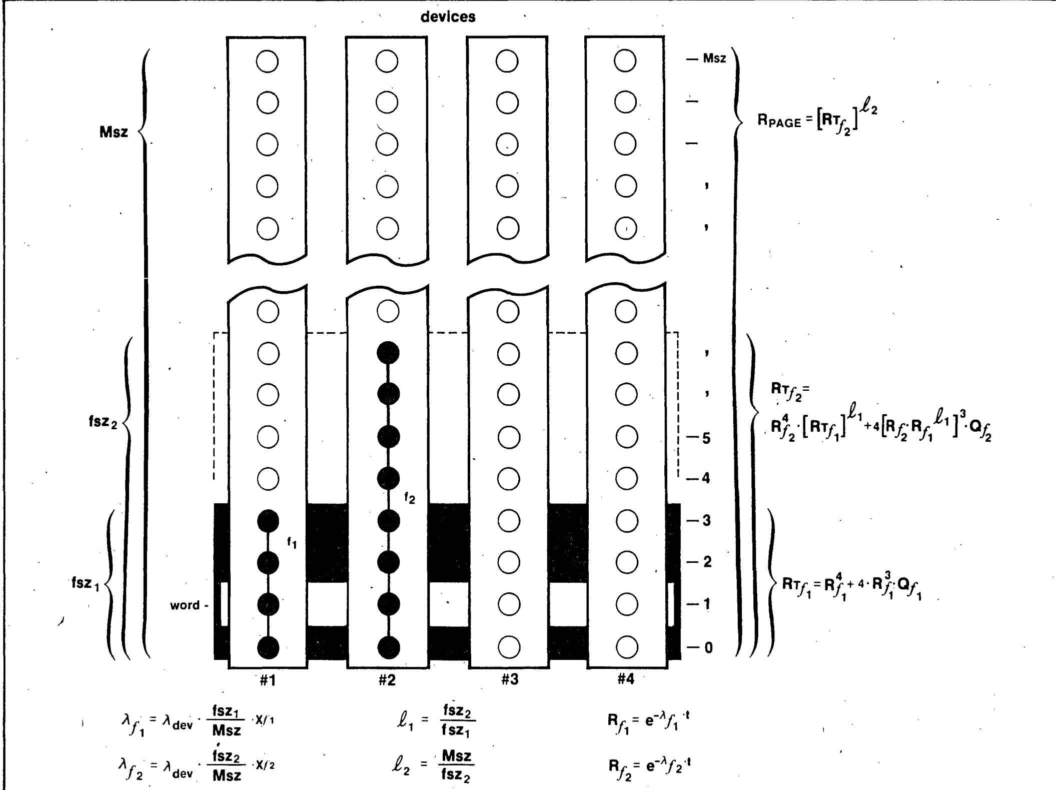


Figure 14. Multiple Failure Type Illustration

Now that the binomial equation technique has been applied to a single failure type, let's expand the process to cover more than one failure type. By the process of combining or permutating these failure types, the Reliability Function can be calculated. Figure 14 shows a four component system with the probability that two failure types f_1 or f_2 can occur in each component. Both failure types affect fsz_1 and fsz_2 number of cells during a failure, respectively. The calculation begins with evaluating the probability of f_1 occuring (EQ:14a) and merging by a second calculation the probability of failure type f_2. (EQ:14b).

EQ:14a $RT_1 = R_{f1}^{\eta} + \eta R_{f1}^{\eta-1} \cdot Q_{f1}$

EQ:14b $RT_2 = R_{f2}^{\eta} \cdot [RT_1^{\ell 2}] + \eta [R_{f2} \cdot R_{f1}^{\ell 2}]^{\eta-1} \cdot Q_{f2}$

NOTE: with λ_{dev} representing more than one failure type, f_1 and f_2, λ_{dev} must be proportioned to the "failure-type-distribution" in determining the unit failure rates λf_1 and λf_2. The term Xf_1 and Xf_2 are introduced to quantify the failure type distribution as a percentage. (Ref: EQ:1 and Figure 5).

EQ:14c is the unit failure rate equation for f_1 and f_2 in this case.

EQ:14c

$$\lambda f_1 = \lambda_{dev} \cdot Xf_1 \cdot \frac{fsz_{f1}}{Msz} \qquad \lambda f_2 = \lambda_{dev} \cdot Xf_2 \cdot \frac{fsz_{f2}}{Msz}$$

The total reliability for the page in Figure 13b is given by equation 14d.

EQ:14d $R(t)_{page} = [RT_2]^{\frac{Msz}{fsz_2}}$

By expanding on this process the equation for a system of memory components with these failure types: f_1, f_2, f_3 is given in EQ:15.

EQ:15

$$RT_3 = R_{f3}^{\eta} \cdot [RT_2]^{\ell 3} + \eta [R_{f3}(R_{f2}(R_{f1})^{\ell 2})^{\ell 3}]^{\eta-1} \cdot Q_{f3}$$

We can now formulate a general set of equations for multiple (f_i) failure types in an error corrected system.

5.2.1 EQUATIONS FOR THE MODEL

The full model under analysis in this report has six failure types, as described in the section on Error Classification. The reliability calculations for a page of memory must permutate all combinations of these six failure types. It is accomplished by the set of equations in EQ:16.

EQ:16

$$\left[\; i \xleftarrow{} \Bigg|_{1}^{N} \begin{array}{l} \ell_i = \dfrac{fsz_i}{fsz_{i-1}} \\ \lambda f_i = \lambda_{dev} \cdot X_i \cdot \dfrac{fsz_i}{Msz} \end{array} \;\right]$$

$$R(t)_{PAGE_{ecc}} = \left\{ i \xleftarrow{} \Bigg|_{1}^{N} \begin{array}{l} R_i = e^{-\lambda f_i \cdot t},\ Q_i = 1 - R_i \\ RS_i = R_i \cdot (RS_{i-1})^{\ell_i} \\ RT_i = R_i^{\eta} \cdot (RT_{i-1})^{\ell_i} + \eta (RS_i)^{\eta-1} \cdot Q_i \end{array} \right\}^{\frac{Msz}{fsz_N}}$$

$$R(t)_{SYSTEM\,ecc} = [R(t)_{PAGE\,ecc}]^{Pages}$$

restrictions: $RS_0 = RT_0 = fsz_0 = 1.$

The process begins at the word level with soft errors and gradually increases the area of evaluation to single cell hard failures, then row or column failures, combined row/column failures, half-chip failures, and finally full-chip failures.

Illustrated in Figures 15 and 16 are the six iterative steps to merge all combinations of failure types — $f_1, f_2, f_3, f_4, f_5, f_6$.

The first step calculates the chance of a single word of the memory page not having more than one soft error.

The second step calculates the probability of not having more than one single-cell hard failure and merges step #1, for a combined result that no more than one failure caused by either soft error or single-cell failure has occurred within the single word analyzed.

The third step calculates for row failures and merges with step #2 all combinations of the three failure types. Using the 2117 example memory system from Figure 6 to illustrate this point — a row or column failure affects 128 memory words — the combined result from step #2, which analyzed a single word, is raised by the exponent 128 as a series equation. The combined result for step #3 is the probability of not having a system failure due to any of the failure types f_1, f_2, f_3, in any given word for a 128-word block.

This process continues up to step six, which is the calculation for all six failure types occuring in all combinations that would cause a system failure within the page of memory. The analysis of each step therefore raises the results of each previous step by the exponent ℓ_i.

5.2.2 THE ENHANCEMENT FACTOR

5.2.2.1 Mean Time Between Failures

The Mean Time Between Failures (MTBF) for a memory system, with or without ECC, is given in EQ:17. MTBF is calculated by integrating the system reliability function, $R(t)_{sys}$, from $t = 0$ to infinity.

EQ:17 $$MTBF_{sys} = \int_0^{\infty} R(t)_{sys} \cdot dt$$

On the average a system will fail once every $MTBF_{sys}$ hours. The relationship between MTBF and the R function is shown in Figure 17.

The bottom line conclusions on the effect that error-correction has on a given memory system is calculated by comparing the resultant $MTBF_{sys-ecc}$ projection with the $MTBF_{sys-necc}$ of a similar system without ECC. The improvement of a memory system with error correction logic over a comparable system without is expressed by EQ:18 as the enhancement factor EF.

EQ:18 $$EF = \frac{MTBF_{sys\text{-}ecc}}{MTBF_{sys\text{-}necc}}$$

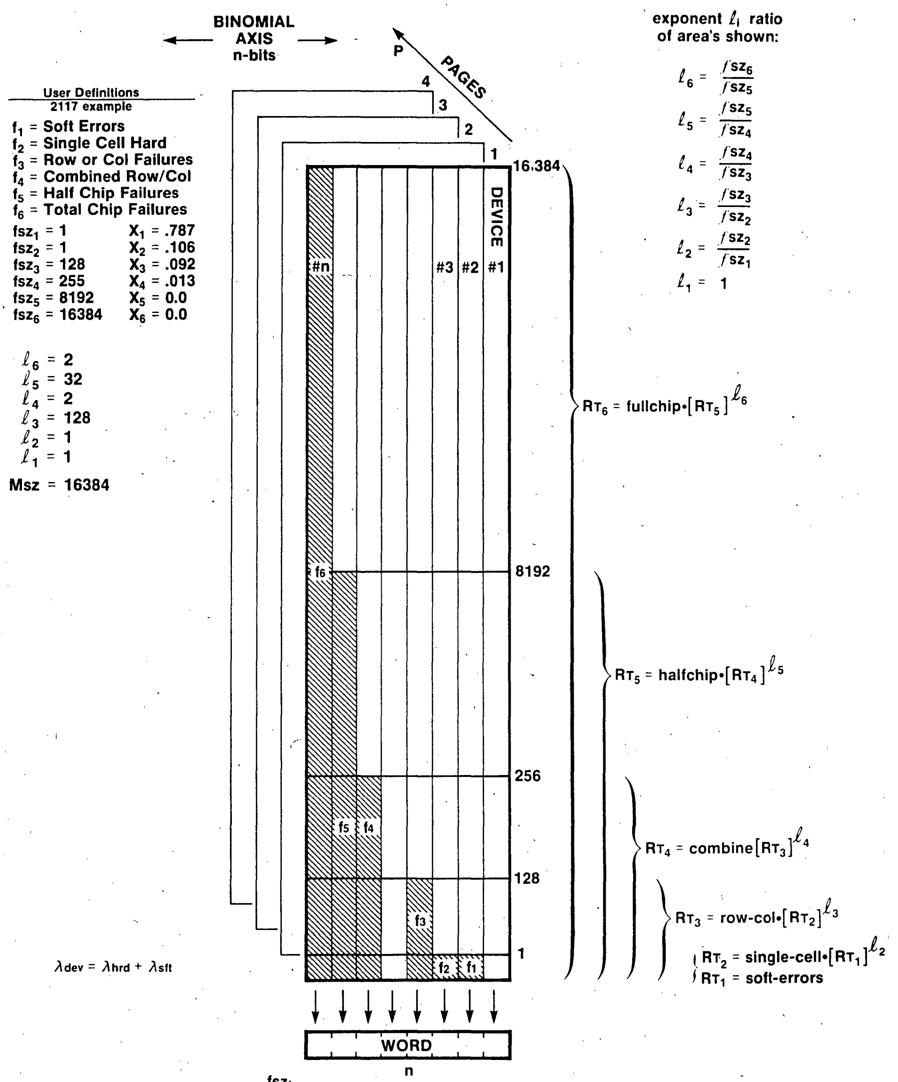
5.2.2.2 Mean Time To Failures

The Mean Time To Failure (MTTF) is similar in concept to MTBF, but differs in that it represents the effects of maintenance on an error corrected memory system. When a maintenance policy is adopted which allows for the replacement of failed components before the system fails, system failure is postponed (depending on how often the system is inspected and maintained). With this policy a memory system fails less frequently than it does without maintenance; it is assured that every new operating period after inspection starts with full redundancy restored. The maintained system Mean Time To Failure thus becomes greater than $MTBF_{sys}$.

If preventive maintenance is performed at an arbitrary time T, then EQ:19 expresses mean time to failure.

EQ:19

$$MTTF = \frac{\int_0^{T} R(t)_{sys\text{-}ecc} \cdot dt}{1 - R(T)_{sys\text{-}ecc}}$$



$$\lambda f_i = \lambda_{dev} \bullet X_i \bullet \frac{fsz_i}{Msz}$$

$$R_{PAGE_{ecc}} = \left\{ \begin{array}{c|l} 6 & R_i = e^{-\lambda_i \bullet t},\ Q_i = 1 - R_i \\ i & Rs_i = R_i \bullet (Rs_{i-1})^{\ell_i} \\ 1 & RT_i = \underbrace{R_i^{\eta} \bullet (RT_{i-1})^{\ell_i}}_{\text{1st term}} + \underbrace{\eta\,(Rs_i)^{\eta-1} \bullet Q_1}_{\text{2nd term}} \end{array} \right\} \Rightarrow RT_6 \qquad R_{SYS} = \left[RT_6\right]^P$$

Figure 15.

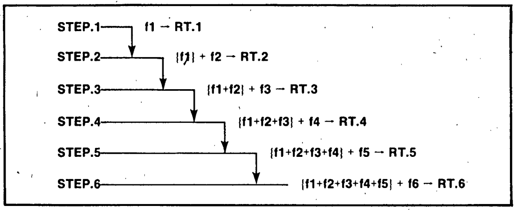


Figure 16.

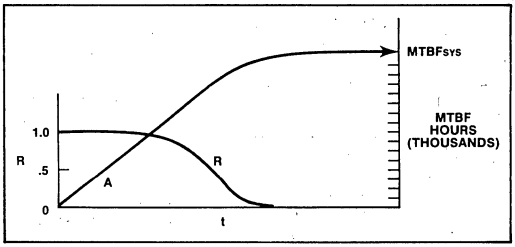


Figure 17.

Figures 18 and 19 show the relationship of MTTF to the R function and MTTF to MTBF respectively.

The enhancement of a memory system with maintenance over a comparable system without ECC is expressed in EQ:20.

EQ:20
$$EF_{mnt} = \frac{MTTF}{MTBF_{sys\text{-}ecc}}$$

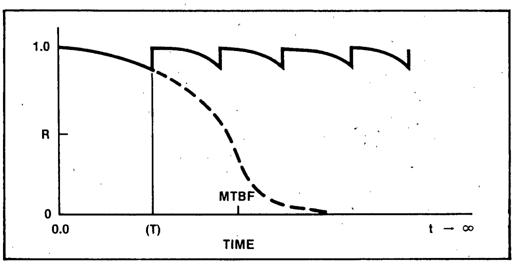


Figure 18.

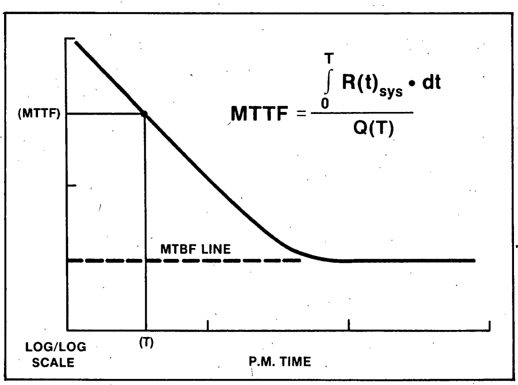


Figure 19.

5.2.3 SOFT ERROR SCRUBBING

In the previous sections on MTBF and MTTF, soft errors and hard errors were treated the same. They both accumulated to cause system failure or were removed at scheduled preventive maintenance (PM) intervals.

However, soft errors can have their own special maintenance function. Recall that soft errors can be purged from a system with ECC by rewriting (restoring) the correct data bit information to the failing memory cell. (Provided that no other bit within the word containing the soft error has failed.) Thus it is possible for the system to maintain itself by software, etc. This special maintenance function of scrubbing soft errors at predetermined intervals is incorporated into the system reliability equations by merely resetting the time parameter t for the soft error portion of the equations.

Figure 20 shows the relationship of soft error scrubbing on MTBF and the system R functions.

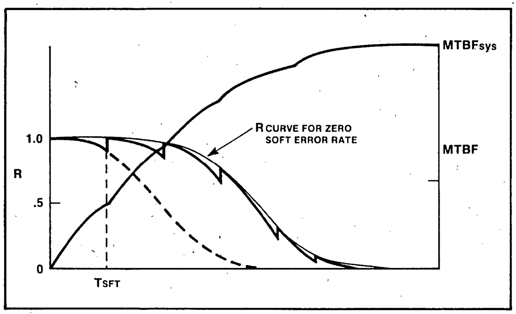


Figure 20.

5.2.4 APPLYING THE MODEL EQUATIONS

The basic set of equations for a model are derived from EQ:16. The application of these equations is best suited for implementation on a computer. An example computer program is available on request.

Figure 21 illustrates a simplified block diagram of the model.

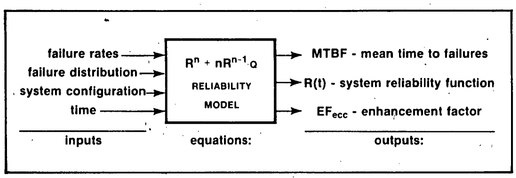


Figure 21.

The required user inputs are for component parameters — total memory size, number of rows and columns, hard failure rate, soft error rate, and

failure mode distribution; for system parameters — memory word size, ECC check bits, number of pages, interval of time, and soft error scrub time.

Output is a set of discrete values of the reliability function representing the complete memory system as a function of time.

The integral functions for MTTF and MTBF are evaluated by the trapezoidal rule of integration.

EQ:21

$$MTBF = \sum_{i=1}^{\infty} \tfrac{1}{2} \cdot [R_{sys_{i-1}} + R_{sys_i}] \cdot \Delta Time$$

$$\text{where } R_{sys_0} = 1$$

Based on the Intel® 2117 Dynamic Ram, the following three sections — (I, II, III) — compare various system configurations and failure rate parameters.

I. Table 1 shows the comparison of six memory configurations, ranging from 32K-bytes to 16 Megabytes. The Input parameters used were those listed in Table 2.

Table 1. Memory Configuration versus MTBF

FAILURE RATE = .127% / 1000 hrs			
configuration	MTBF, non-ecc	MTBF, ecc	E.F.
16-bit word by 1 pg	49 k hrs	1170 k hrs	24
16-bit word by 128 pgs	390 hrs	95 k hrs	249
32-bit word by 1 pg	24 k hrs	658 k hrs	27
32-bit word by 128 pgs	195 hrs	53 k hrs	278
64-bit word by 1 pg	12 k hrs	355 k hrs	29
64-bit word by 128 pgs	98 hrs	29 k hrs	299

Table 2. Model Input Parameters

Combined HARD FAILURE RATE = 0.027% / 1000 hours	
Failure distributions:	
single cell	= 50.0%
row cells	= 15.6%
column cells	= 28.1%
row-column cells	= 6.3%
half-chip	= 0.0%
full-chip	= 0.0%
total	100%
SOFT ERROR FAILURE RATE = 0.1% / 1000 hrs - est.	

These results show an enhancement factor of approximately 27 for a single page of memory and over 278 for 128 pages.

II. Table 3 shows the comparison of six memory configurations, between two soft error rates.

Table 3. Memory Configurations versus SE Rates

HARD FAILURE RATE = 0.027% / 1000 hrs		
	SOFT ERROR RATE .2% / 1000 hrs	SOFT ERROR RATE .5% / 1000 hrs
configuration	MTBF, ecc	MTBF, ecc
16-bit word by 1 pg	880 k hrs	575 k hrs
16-bit word by 128 pgs	70 k hrs	44 k hrs
32-bit word by 1 pg	492 k hrs	322 k hrs
32-bit word by 128 pgs	39 k hrs	24 k hrs
64-bit word by 1 pg	265 k hrs	173 k hrs
64-bit word by 128 pgs	21 k hrs	13 k hrs

III. Table 4 shows the comparison of a memory device with one failure type. The failure types compared are devices with a single cell failure modes and full-chip failure modes.

System A has devices with only "single cell" failure types and System B has only "full-chip" type. All other parameters are identical. Both system failure rates are 0.027%/1000 hrs.

Table 4. Single Cell versus Full Chip Failures

configuration:	SYSTEM A with single cell MTBF	SYSTEM B with full-chip MTBF
64-bit by 1 page	8.3 m hrs	103 k hrs
64-bit by 128 pages	730 k hrs	6 k hrs

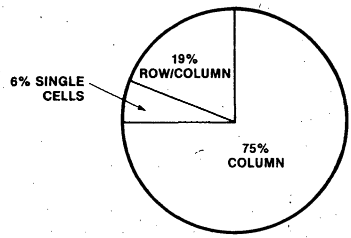
5.2.5 DISTRIBUTION

Error correction in a system does not alter or change the actual occurrence of failures. Failures still occur at the $MTBF_{necc}$ period based on the distribution in Figure 5. (For the example system, the soft error rate is three times the hard failure rate — .1% vs. .027% — which represents a soft error occurring 78% of the time.)

However, the fact that a multibit failure is required to cause a system failure in a system with ECC modifies the failure distribution; soft errors have much less effect than hard failures on system performance. Figure 22 demonstrates this by showing a modified distribution based on average cells per failure, the Rate Geometry Product, RGP.

INDIVIDUAL FAILURE RATE DISTRIBUTION OF A GIVEN TYPE
TIMES THE NUMBER OF CELLS AFFECTED
EQUALS AVERAGE CELLS PER FAILURE

FAILURE TYPE	% DISTRIBUTION		CELLS		AVERAGE CELLS
SOFT ERROR:					
SINGLE CELL	78.7%	×	1	=	0.79
HARD ERRORS:					
SINGLE CELL	10.6%	×	1	=	0.11
ROW	6.0%	×	128	=	7.93
COLUMN	3.4%	×	128	=	4.35
ROW/COLUMN	1.3%	×	256	=	3.32
	100%		TOTAL		16.5



DISTRIBUTION BY NUMBER OF AVERAGE CELLS

Figure 22.

The illustration shows the statistical average cell failure for each type derived by taking the product of the component failure rate distribution times the number of cells affected. For the 2117 example device, the total average cell failure is 16.2 of which 11.8 are column and row failures.

Intuitively, it can be seen that row and column failures are the most predominant, while the least predominant are soft errors and single cell hard errors.

6. SUMMARY

This Application Note presents step-by-step procedures for calculating system reliability. In a system without ECC, a fault of any type can cause system failure — predominantly types with the highest failure rates. In a system with ECC, only multi-bit errors within the same word cause system failure — predominantly types with the highest average cell errors as defined by the Rate Geometry Product. An Enhancement Factor, comparing a system without ECC to one with ECC, can be used to determine if error correcting techniques are advantageous for any specific memory system.

References

1. Randall C. Cork, "Reliability with Error-Detecting and Correcting Codes in Semiconductor Memories," Ph.D. dissertation, Arizona State University, 1975.
2. Bertram L. Amstadter, Reliability Mathematics Fundamentals; Practices; Procedures, McGraw Hill, N.Y., 1971.
3. Byron L. Newton, Statistics for Business, Science Research Associates, 1973.
4. Carl-Erik W. Sundberg, member IEEE, "Erasure and Error Decoding for Semiconductor Memories", IEEE 1978.
5. Peter Elias, "Error Free Coding", MIT.
6. S.K. Wang & K. Lovelace, "Improvement of Memory Reliability by Single-Bit-Error Correction", Texas Instruments Inc.

APPENDIX A

APPENDIX A

EQ:1a $\lambda_{hrd} = \lambda_{single} + \lambda_{row} + \lambda_{column} + \lambda_{row/col} + \lambda_{halfchip} + \lambda_{fullchip}$

EQ:1b $\lambda_{dev} = \lambda_{hrd} + \lambda_{sft}$

EQ:2 $R(t) = e^{-\lambda t}$

EQ:3 $R(t)_{sys} = R(t)_1 \cdot R(t)_2 \cdot R(t)_3 \cdot, \;, \;, R(t)_\eta$
where $R(t)_i = e^{-\lambda_i \cdot t}$

EQ:4 $R(t)_{sys} = R(t)^\eta = e^{-\eta\lambda t}$

EQ:5 $a^\eta + \eta a^{\eta-1} \cdot b + \frac{\eta(\eta-1)a^{\eta-2} \cdot b^2}{2!} + \frac{\eta(\eta-1)(\eta-2)a^{\eta-3} \cdot b^3}{3!} + \cdots + b^\eta$

EQ:6 $R(t) + Q(t) = 1$, then $Q(t) = 1 - R(t)$

EQ:7 $[R + Q]^\eta = 1$

EQ:8 $R^\eta + \eta R^{\eta-1} \cdot Q + \frac{\eta(\eta-1)R^{\eta-2} \cdot Q^2}{2!} + \frac{\eta(\eta-1)(\eta-2)R^{\eta-3} \cdot Q^3}{3!} + \cdots + Q^\eta = 1$

EQ:9 $R_T(t) = \underbrace{R^\eta}_{1st} + \eta \cdot \underbrace{R^{\eta-1} \cdot Q}_{2nd}$ – binomial terms

EQ:10 $R(t)_{system} = [R(t)_{page}]^P$

EQ:11 $R(t)_{PAGE_{necc}} = R(t)^\eta_{DEV_{necc}} = e^{-\lambda \cdot n \cdot t}$

EQ:12 $R(t)_{SYS_{necc}} = [R(t)_{PAGE_{necc}}]^P = [R(t)_{DEV}]^{P \cdot \eta}$

EQ:13 $R(t)_{PAGEecc} = \left[R(t)_x^\eta + \eta \cdot R(t)_x^{\eta-1} \cdot Q(t)_x\right]^{\ell_x}$

EQ:14a $R_{T_1} = R_{f_1}^\eta + \eta R_{f_1}^{\eta-1} \cdot Q_{f_1}$

EQ:14b $R_{T_2} = R_{f_2}^\eta \cdot [R_{T_1}^{\ell_2}] + \eta [R_{f_2} \cdot R_{f_1}^{\ell_2}]^{\eta-1} \cdot Q_{f_2}$

EQ:14c $\lambda f_1 = \lambda_{dev} \cdot X f_1 \cdot \frac{fsz_{f_1}}{Msz}$ $\qquad \lambda f_2 = \lambda_{dev} \cdot X f_2 \cdot \frac{fsz_{f_2}}{Msz}$

EQ:14d $R(t)_{page} = [R_{T_2}]^{\frac{Msz}{fsz_2}}$

EQ:15 $R_{T_3} = R_{f_3}^\eta \cdot [R_{T_2}]^{\ell_3} + \eta[R_{f_3}(R_{f_2}(R_{f_1})^{\ell_2})^{\ell_3}]^{\eta-1} \cdot Q_{f_3}$

EQ:16

$$\left[i \xleftarrow{} \begin{array}{l|l} N & \ell_i = \frac{fsz_i}{fsz_{i-1}} \\ 1 & \lambda f_i = \lambda_{dev} \cdot X_i \cdot \frac{fsz_i}{Msz} \end{array} \right]$$

$$R(t)_{PAGE_{ecc}} = \left\{ i \leftarrow \begin{array}{l|l} N & R_i = e^{-\lambda f_i \cdot t},\ Q_i = 1 - R_i \\ & RS_i = R_i \cdot (RS_{i-1})^{\ell_i} \\ 1 & RT_i = R_i^\eta \cdot (RT_{i-1})^{\ell_i} + \eta (RS_i)^{\eta-1} \cdot Q_i \end{array} \right\}^{\frac{Msz}{fsz_N}}$$

$$R(t)_{SYSTEM\,ecc} = [R(t)_{PAGE\,ecc}]^{Pages}$$

restrictions: $RS_0 = RT_0 = fsz_0 = 1.$

EQ:17 $$MTBF_{sys} = \int_0^{\infty} R(t)_{sys} \cdot dt$$

EQ:18 $$EF = \frac{MTBF_{sys\text{-}ecc}}{MTBF_{sys\text{-}necc}}$$

EQ:19 $$MTTF = \frac{\int_0^{T} R(t)_{sys\text{-}ecc} \cdot dt}{1 - R(T)_{sys\text{-}ecc}}$$

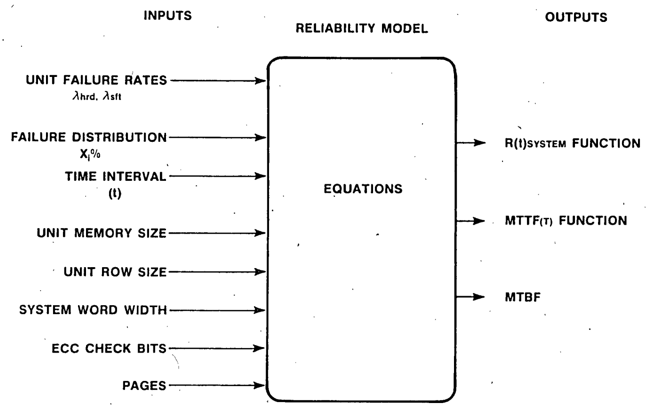
EQ:20 $$EF_{mnt} = \frac{MTTF}{MTBF_{sys\text{-}ecc}}$$

EQ:21 $$MTBF = \sum_{i=1}^{\infty} \tfrac{1}{2} \cdot [R_{sys_{i-1}} + R_{sys_i}] \cdot \Delta Time$$

where $R_{sys_0} = 1$

APPENDIX B

APPENDIX B



INPUTS
RELIABILITY MODEL
OUTPUTS
UNIT FAILURE RATES
λhrd, λsft
FAILURE DISTRIBUTION
Xi%
TIME INTERVAL
(t)
UNIT MEMORY SIZE
UNIT ROW SIZE
SYSTEM WORD WIDTH
ECC CHECK BITS
PAGES
EQUATIONS
R(t)SYSTEM FUNCTION
MTTF(T) FUNCTION
MTBF

FORTRAN IV V02.04

```
      C########################################################
      C     #     ECC RELIBILITY MODEL    REV 6B  FEB79      #
      C     #                                                 #
      C     #     INTEL CORP                                  #
      C     #     MEMORY PRODUCTS DIVISION                    #
      C     #     APPLICATIONS LAB                            #
      C     #     ALOHA, OREGON                               #
      C     #                                                 #
      C     #                                                 #
      C     #     ERROR CORRECTION RELIABILITY
      C     #     APPLICATIONS NOTE                           #
      C     ###############################################
      C
            IMPLICIT REAL*8 (D,R,S,T,Z)
            DIMENSION KM(2),LH(2),KL(4),LQ(4)
            BYTE LL(2),LR(2),IBUF(80),ILIST(80)
            INTEGER*4 IIPTR,LPTR(13),IABORT,IHELP,LMFLGS(3),IIXFG
            COMMON /ECC1/RXZ,RXS,RXR,RXC,RXF,RXE,RXH,RXT,RCNF,SZER,SXX
            COMMON /ECC2/RMSZ,RCSZ,RWD,BPG,RZD,RZDD,REC,RZER,R1,RTM,RTSF
            COMMON /ECC3/IM,ILLM,IULM,RSQ,JSFLG,EPGX,ISFLG,ST,R,RTH,R2
            COMMON /ECC4/ISW,RFF,IPM,RTTF,RZTTL,ICST,RALMT,IDBK,IQFG,IUCD
            COMMON /ECC5/ISFG,REC1,REC2,IEFLG,RZSYS,ILIM,IDFLG,RAVE
            COMMON /ECC6/ITIN,ITOUT,ILP
            COMMON /ECC7/RZZ,RZS,RZR,RZC,RZF,RZE,RZH,RZT,RZDX
            COMMON /ECC8/ECZ,ECS,ECR,ECC,ECF,ECE,ECH,ECT,ECX
            COMMON /ECC9/EW,EW1,EW2,RW,RW1,RW2,S,T,TSFT,THRD
            COMMON /ECCA/EPG,EBD,EPSZ,ECA,EPX,EPY,EPZ
            COMMON /ECCC/I,IMN,RPRT,RTO,RTPG,RTX,RZDZ,RXX,RSPC1,RSPC2
            DATA KL/'  ','* ',' $','*$'/,IABORT/'ABOR'/,IHELP/'HELP'/
            DATA KM/'KB','MB'/,LL/' ','<'/,LR/' ','>'/
            DATA LMFLGS/'SYS','MPD','MSO'/
      C                  1      2      3      4      5      6      7
            DATA LPTR/'LIST','SIZE','RATE','DIST','COMM','DUMP','FLAG',
           * 'HXDR','CYCL','PURG','NECC','SECC','DECC'/
      C       8      9      10     11     12     13
            DATA LQ/'Q1','Q2','QX','QZ'/
            DATA LH/' -','M-'/,IBEL/1799/
            DATA ITIN/5/,ITOUT/7/,ILIM/10/,IDFLG/1/,ILP/6/
            DATA RXZ/.7874D0/,RXS/.50D0/,RXR/.156D0/,RXC/.281D0/,RXE/.062D0
            DATA RXH/0.0D0/,RXT/0.0D0/,RCNF/.37D0/,SZER/.1D-4/
            DATA RRXS/50.D0/,RRXR/15.6D0/,RRXC/28.1D0/,RRXE/6.2D0/
            DATA RRXH/0.0D0/,RRXT/0.0D0/,SXX/1.0D0/
            DATA RMSZ/16384.0D0/,RCSZ/128.0D0/,RWD/64.0D0/,BPG/128.0/
            DATA RZD/0.00027D0/,RZSE/0.001D0/,REC/-1.0D0/,RZER/0.0D0/
            DATA RRZD/0.027D0/,RRZSE/0.1D0/,RRZTTL/0.0D0/,RRZSYS/0.0D0/
            DATA R1/1.0D0/,RTM/2500.0D0/,RTSF/1000.0D0/,RAVE/228.0D0/
            DATA IM/0/,ILLM/0/,IULM/30/,RSQ/2.0D0/,JSFLG/1/,EPGX/1.0/
            DATA ISFLG/1/,ST/0.0D0/,R/100.0D0/,RTH/100000.0D0/,R2/2.0D0/
            DATA ISW/1/,RFF/0.0D0/,IPM/10/,RTTF/0.0D0/,RZTTX/0.0D0/
            DATA ICST/2/,RALMT/0.01D0/,IDBK/1/,IQFG/1/,IUCD/0/,ISFG/1/
            DATA REC1/8.0D0/,REC2/15.0D0/,IEFLG/0/,RZSYX/0.0D0/
            DATA ILFG/1/,RTMSO/0.0D0/,RZTMP/0.0D0/,JXFG/1/
            DATA RZS1/0.0D0/,RZS2/0.0D0/,RRZS1/0.0D0/,RRZS2/0.0D0/
            DATA TTMCYL/5.0D2/,TMCYL/5.0D2/,TTRCYL/1.5D4/,TRCYL/1.5D4/
```

```
FORTRAN IV        V02.04

0039          DATA TREF/7.D3/,RRX1A/66.D0/,RX1A/.66D0/,RRX1B/33.D0/,RX1B/.33D0/
0040          RPSZ=RZER
0041          SLM=RZER
0042          EPG=BPG
      C
      C#################### RELIABILITY EQUATIONS ###########################
      C
      C     R[T] = N*QT*[ RT*(RE*(RF*(RS*(RZ)**MS)**MF)**ME)**MT ]**(N-1)  +
      C
      C         (RT**N)*[ N*QE*[ RF*(RF*(RS*(RZ)**MS)**MF)**ME ]**(N-1)  +
      C
      C         (RE**N)*[ N*QF*[ RF*(RS*(RZ)**MS)**MF ]**(N-1)  +
      C
      C            (RF**N)*[ N*QS*[ RS*(RZ)**MS ]**(N-1)  +
      C
      C              (RS**N)*[ N*QZ*[ RZ ]**(N-1)  +
      C
      C                    (RZ**N) ]**MS ]**MF ]**ME ]**MT
      C
      C     WHERE:  RZ = SOFT ERROR              RS = SINGLE CELL
      C         RF = COLUMN                  RE = ROW /COLUMN
      C         RH = HALF CHIP               RT = TOTAL CHIP
      C
      C         MS -> SINGLE CELL TO SOFT ERROR RATIO  - 1
      C         MF = COLUMN TO SINGLE CELL RATIO
      C         ME = ROW/COLUMN TO COLUMN RATIO
      C         MH = HALF CHIP TO ROW/COLUMN RATIO
      C         MT = TOTAL CHIP TO HALF CHIP RATIO
      C
0043          WRITE (ITOUT,10)
0044     10   FORMAT (T2,'<<<< ERROR CORRECTION RELIABILITY >>>>',/,
            C T4,'INTEL CORP.  MPD/MCO    DJM FEB79',//,
            C T4,'FOR PROGRAM DESCRIPTION ENTER >  HELP')
      C####################################################################
      C
      C                       INPUT PARAMETERS
      C
      C####################################################################
      C
0045    100   CONTINUE
0046          WRITE (ITOUT,90) IBEL
0047     90   FORMAT (A2,T5,'POINTER, INDEX, TIME., PAGE, BOARD')
0048    101   FORMAT (T2,'** LIST OUTPUT PARAMETERS **',/,
            C T2,'* LOWER, UPPER, SKIP, UNCOND, MAINT, .CONF')
0049    102   FORMAT (T2,'** COMPONENT & MEMORY SYSTEM PARAMETERS **',/,
            C T2,'* RAMSIZE., COLSIZE, WORDSIZE, CHECKBITS')
0050    103   FORMAT (T2,'** DEVICE & SYSTEM FAILURE RATES **',/,
            C T2,'* .HARD%, .SOFT%, .TTL%, .SYSTEM%')
0051    104   FORMAT (T2,'** DEVICE HARD FAILURE TYPE DISTRIBUTION **',/,
            C T5,'HINT: SC ROW COL CMB HLF FULL',/,
            C T2,'* X2.%, X3.%, X4.%, X5.%, X6.%, X7.%')
0052    105   FORMAT (T2,'** HEADER COMMENT **',/,T2,'*')
0053    106   FORMAT (T2,'#')
0054    107   FORMAT (T2,'** ERROR **',1X,I2)
```

```
 109  FORMAT (T2,'** CYCLE **      SE CYCLES & DISTRIBUTION'
     C ,/,T5,'SOFT ERROR ALGORITHM - CYCLES IN NS',/,
     C T2;'* MEMORY.  REFRESH.  BITLINE. %  SNGLE-CELL. %',/,T2,'*')
C
      READ (ITIN,95) IIPTR,III,RRTM,IRPG,IRBD
  95  FORMAT (A4,1X,I6,F10.2,I5,I5)
      IPTR=0
      DO 94,J=1,13
      IF (IIPTR.EQ.LPTR(J)) IPTR=J
  94  CONTINUE
      IF (IIPTR.EQ.IABORT) STOP
      IF (IIPTR.EQ.IHELP) CALL HELP
      IF (IPTR.EQ.0) GO TO 100
      IF (IPTR.LT.10) GO TO 96
      RTM=RRTM
      EPG=IRPG
      EBD=IRBD
      I=III
C    ..... DETERMINE WHAT TEST .....
      IMM=IPTR-10
  96  CONTINUE
      IDMP=1
      IF (IPTR.EQ.6) IDMP=2
      IF (IPTR.GE.11) GO TO 200
      GO TO (98,115),IDMP
  98  CONTINUE
      GO TO (110,120,130,140,150,160,170,180,190,195),IPTR
 110  WRITE (ITOUT,101)
      READ (ITIN,112) ILLM,IULM,ISW,IUCD,JS,RCNF
 112  FORMAT (5(I6),F10.8)
C    ... DISABLE FUDGE FACTOR ...
      RFF=0.0
      IEFLG=0
      IF ((ILLM.LE.0).OR.(IULM.LE.0).OR.(JS.LT.0)) IEFLG=1
      IF ((RCNF.LE.0.0).OR.(RFF.LT.0.0)) IEFLG=2
      IF ((IUCD.LT.0).OR.(JS.LT.0)) IEFLG=3
      IF (IEFLG.EQ.0) GO TO 100
      WRITE (ITOUT,107) IEFLG
 115  WRITE (ITOUT,117) LPTR(1),ILLM,IULM,ISW,IUCD,JS,RCNF,RFF
 117  FORMAT (T2,A4,':  ',5(I6,1X),F10.8,1X,F8.0)
      WRITE (ITOUT,106)
      GO TO (100,125),IDMP
C
 120  CONTINUE
      WRITE (ITOUT,102)
 121  READ (ITIN,122) RMSZ,JCSZ,JWD,JEC
 122  FORMAT (F8.0,3(I5))
      IEFLG=0
      IF ((RMSZ.LT.1.).OR.(JCSZ.LT.1).OR.(JWD.LT.1)) IEFLG=
      RCSZ=JCSZ
      RWD=JWD
      REC=JEC
      IF (IEFLG.EQ.0) GO TO 100
      WRITE (ITOUT,107) IEFLG
```

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```
 125  WRITE (ITOUT,127) LPTR(2),RMSZ,JCSZ,JWD,JEC
 127  FORMAT (T2,A4,': ',F8.0,1X,3(I5,1X))
      WRITE (ITOUT,106)
      GO TO (100,135),IDMP
 130  CONTINUE
      WRITE (ITOUT,103)
      READ (ITIN,132) RRZD,RRZSE,RRZTTL,RRZSYS
 132  FORMAT (4(F12.8))
      IEFLG=0
      IF ((RRZD.EQ.0.0).AND.(RRZSE.EQ.0.0)
     * .AND.(RRZTTL.EQ.0.0).AND.(RRSYS.EQ.0.0)) IEFLG=1
      IF ((RRZTTL.LT.0.0).OR.(RRZSYS.LT.0.0).OR.(RRZD.LT.0.0)
     1 .OR.(RRZSE.LT.0.0)) IEFLG=2
      IF (IEFLG.EQ.0) GO TO 136
      WRITE (ITOUT,107) IEFLG
 135  WRITE (ITOUT,137) LPTR(3),RRZD,RRZSE,RRZTTL,RRZSYS
 137  FORMAT (T2,A4,': ',4(F12.8,1X))
      WRITE (ITOUT,106)
      GO TO (100,145),IDMP
C     ... CONVERT FROM PERCENT ...
 136  RZD=RRZD/100.
      RZSE=RRZSE/100.
      RZTTX=RRZTTL/100.
      RZSYX=RRZSYS/100.
      GO TO 100
 140  CONTINUE
      WRITE (ITOUT,104)
      READ (ITIN,142) RRXS,RRXR,RRXC,RRXE,RRXH,RRXT,RPSZ
 142  FORMAT (6(F11.8),F8.0)
C     .... DISABLE PARTIALS ....
      RPSZ=0.0
      IEFLG=0
      RXS=RRXS/100.
      RXR=RRXR/100.
      RXC=RRXC/100.
      RXE=RRXE/100.
      RXH=RRXH/100.
      RXT=RRXT/100.
      SXX=RXS+RXR+RXC+RXE+RXH+RXT
      IF (SXX.GT.R1) IEFLG=1
      IF (RPSZ.LT.0.0) IEFLG=2
      IF (IEFLG.EQ.0) GO TO 100
      WRITE (ITOUT,107) IEFLG
 145  WRITE (ITOUT,147) LPTR(4),RRXS,RRXR,RRXC,RRXE,RRXH,RRXT,RPSZ
 147  FORMAT (T2,A4,': ',6(F10.6,1X),F8.0)
      WRITE (ITOUT,106)
      GO TO (100,155),IDMP
 150  WRITE (ITOUT,152)
 152  FORMAT (T2,'* INPUT BUFFER')
      READ (ITIN,154) ICHRS,(IBUF(IB),IB=1,ICHRS)
 154  FORMAT (T2,Q,72A1)
      GO TO 100
 155  WRITE (ITOUT,156) LPTR(5),(IBUF(IB),IB=1,72)
 156  FORMAT (T2,A4,': ',72A1)
```

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```
0172           GO TO (100,193),IDMP
0173     160   CONTINUE
0174     170   CONTINUE
         C     FLAGS
0175           WRITE (ITOUT,172)
0176     172   FORMAT (T2,'* FLAGS -  SET TTL & SYSTEM FAILURE RATE MODE',
              C /,T10,'- & FLAG FOR ONE OR TWO DIMENSION MERGE',/,
              C T2,'* NNN, Q#')
0177           READ (ITIN,173) IIXFG,IIQFG
0178     173   FORMAT (A3,1X,A2)
0179           IEFLG=0
0180           JXFG=0
0181           DO 174 IJ=1,3
0182           IF (IIXFG.EQ.LMFLGS(IJ)) JXFG=IJ
0184           IF (IIQFG.EQ.LQ(IJ)) IQFG=IJ
0186     174   CONTINUE
0187           WRITE (ITOUT,179) LMFLGS(JXFG),LQ(IQFG),IIXFG,IIQFG
0188     179   FORMAT (T2,'##SPECIAL CK ->',2X,A3,1X,A2,5X,A3,1X,A2,/)
0189           IF ((IQFG.LT.1).OR.(IQFG.GT.3)) IEFLG=1
0191           IF ((JXFG.LT.1).OR.(JXFG.GT.3)) IEFLG=2
0193           IF (IEFLG.EQ.0) GO TO 100
0195     175   WRITE (ITIN,176) IEFLG
0196     176   FORMAT (T2,'** ERROR -',I2,' RETRY, HINT: SYS, MPD, OR MSO')
0197           GO TO 170
0198     180   CONTINUE
         C     HEADER
0199           IMM=0
0200           EPG=IRPG
0201           EBD=IRBD
0202           REC=III
0203           WRITE (ITOUT,182) JXFG,REC,EPG,EBD
0204     182   FORMAT (T2,'* HEADER > FLG-',I3,2X,'CK-',F4.0,2X,'PG-',
              C F4.0,3X,'BD-',F4.0)
0205           GO TO 200
0206     190   CONTINUE
0207           WRITE (ITOUT,109)
0208           READ (ITIN,192) TTMCYL,TTRCYL,RRX1A,RRX1B
0209     192   FORMAT (2(F12.0),2(F8.4))
0210           IEFLG=0
0211           IF ((TTMCYL.LE.0.0).OR.(TTRCYL.LE.0.0)) IEFLG=1
0213           IF ((RRX1A+RRX1B).GT.100.) IEFLG=2
0215           IF ((RRX1A.LT.0.).OR.(RRX1B.LT.0.)) IEFLG=3
0217           IF (IEFLG.NE.0) GO TO 193
0219           TMCYL=TTMCYL
0220           TRCYL=TTRCYL
0221           RX1A=RRX1A/100.
0222           RX1B=RRX1B/100.
0223           GO TO 100
0224     193   WRITE (ITOUT,194) TTMCYL,TTRCYL,RRX1A,RRX1B
0225     194   FORMAT (T2,'* ',2(F12.0,1X),2X,2(F8.4,1X))
0226           GO TO 100
0227     195   CONTINUE
         C     PURGE
0228           DO 197,INIT=1,5
```

```
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0229            WRITE (ILP,196) (ILIST(NN),NN=1,72)
0230      196   FORMAT (T2,72A2)
0231      197   CONTINUE
0232            WRITE (ILP,198)
0233      198   FORMAT (1H1)
0234            GO TO 100
      C
      C##########################################################################
      C
      C                       INITIALIZE PARAMETERS
      C
      C###########################################################################
0235      200   CONTINUE
0236            IF (IEFLG.EQ.0) GO TO 202
0238            WRITE (ITIN,201) IEFLG
0239      201   FORMAT (T2,'ERROR COND EXISTS - ABORT ',I2)
0240            GO TO 100
0241      202   CONTINUE
0242            SLM=JS*RTM
0243            RE=0.00
0244            IF (REC.LT.RZER) GO TO 208
0246            RE=REC
0247            GO TO 209
0248      208   CONTINUE
0249            IF (IMM.EQ.2) RE=REC1
0251            IF (IMM.EQ.3) RE=REC2
0253      209   RW=RWD+RE
0254      210   CONTINUE
      C                       ....... NAME CHANGES FOR SPEED REASON'S
0255            EW=RW
0256            RW1=RW-1.0
0257            EW1=RW1
0258            RW2=RW-2.0
0259            EW2=RW2
      C     .... SOFT ERROR ALGORITHM BY CYCLE TIMES ....
0260            SMCYL=RMSZ
0261            SMTIM=SMCYL*TMCYL
0262            SRCYL=SMTIM/TRCYL
0263            SRPG=(EPG*EBD)-1.
0264            SECYL=(SMTIM+(SMTIM*SRPG))/(SMCYL+(SRCYL*SRPG))
0265            SNRMLZ=TREF/SECYL
0266            RZDD=(RX1A*RZSE*SNRMLZ)+(RX1B*RZSE)
0267            IF (JXFG.NE.2) RZDD=RZSE
0269            RZDX=RZD+RZDD
0270            RXZ=RZDD/RZDX
0271            RXF=RXR+RXC
0272            RRSZ=RMSZ/RCSZ
0273            RFSZ=(RCSZ+RRSZ)/2.0
0274            RESZ=RMSZ/(RCSZ+RRSZ)
0275            RHSZ=2.0
0276            RTSZ=1.0
0277            ECZ=1.0
0278            ECS=1.0
0279            ECR=RRSZ
```

```
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0280        ECC=RCSZ
0281        ECF=RFSZ
0282        ECE=(RRSZ+RCSZ)/RRSZ
0283        ECH=RMSZ/((RRSZ+RCSZ)*2.0)
0284        ECT=2.0
0285        T=RZER
0286        S=RZER
0287        RINC=RTM/RTSF
0288        RMTBF=RZER
0289        RMTTF=RZER
0290        RMNT=RZER
0291        LG=1
0292        IMFLG=1
0293        ISFLG=1
0294        JSFLG=1
0295        IXFLG=1
0296        ILFLG=1
0297        RMIL=1000000.
0298        IF (RTM.GE.100000.0) IMFLG=2
0300        RZZ=(RXZ*RZDX)/RMSZ
0301        RZS=(RXS*RZD)/RMSZ
0302        RZR=(RXR*RZD)/RRSZ
0303        RZC=(RXC*RZD)/RCSZ
0304        RZF=(RXF*RZD)/RFSZ
0305        RZE=(RXE*RZD)/RESZ
0306        RZH=(RXH*RZD)/RHSZ
0307        RZT=(RXT*RZD)
0308        RHRD=1.0-RXZ
0309        RTMP=(RXS/RMSZ)+(RXF/RFSZ)+(RXE/RESZ)+(RXH/RHSZ)+(RXT/RTSZ)
0310        RAVE=RXZ+((RTMP*RMSZ)*RHRD)+RFF
0311        AZ=RXZ
0312        AS=RHRD*RXS
0313        AF=RHRD*RXF*(RMSZ/RFSZ)
0314        AE=RHRD*RXE*(RMSZ/RESZ)
0315        AH=RHRD*RXH*(RMSZ/RHSZ)
0316        AT=RHRD*RXT*(RMSZ/RTSZ)
0317        AXX=AS+AF+AE+AH+AT
0318        BZ=(AZ/(AZ+AXX))*R
0319        BHRD=100.00-BZ
0320        BS=(AS/AXX)*R
0321        BF=(AF/AXX)*R
0322        BE=(AE/AXX)*R
0323        BH=(AH/AXX)*R
0324        BT=(AT/AXX)*R
0325        RZDZ=RZDX*(RAVE/RMSZ)
0326        ECA=RMSZ/RAVE
0327        RZREV=0.0
0328        RZTOL=0.0
0329        RTPM=RTM/IPM
0330        ROLD=1.0
0331        ISFLG=1
0332        RTSED=RTTF
0333        RSPC1=1.0
0334        RSPC2=2.0
```

```
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0335         EPX=((RMSZ-RPSZ)/RMSZ)*EPG
0336         EPY=(RPSZ/RMSZ)*EPG
0337         EPZ=0.0
0338         IF (RPSZ.LE.RMSZ) GO TO 211
0340         EP=(RPSZ-RMSZ)/RMSZ
0341         EPZ=EP*EPG
0342         EPY=(1.0-EP)*EPG
0343         EPX=0.0
0344         IF (RPSZ.LE.2.0*RMSZ) GO TO 211
0346         EPX=0.0
0347         EPY=0.0
0348         EPZ=0.0
0349    211  CONTINUE
0350         EPSZ=RPSZ
0351         RZTMP=0.0
0352         IF ((RTTF.NE.RZER).OR.(IMM.EQ.1)) GO TO 212
0354         RZTMP=RWD*EPG*EBD*((RZD*SXX)+RZDD)
0355         IF (RZTMP.GT.0.0) RTSED=1000.0/RZTMP
0357    212  CONTINUE
0358         RZTTL=0.0
0359         RZSYS=0.0
0360         RTMSO=0.0
0361         GO TO (213,214,214),JXFG
        C    NORMAL  TTL SYSTEM CALCULATION.....
0362    213  RZTTL=RZTTX
0363         RZSYS=RZSYX
0364         IF (RZSYS.GT.0.0) RTMSO=1000.0/RZSYS
0366         GO TO 216
        C    MSO MODE  RTMSO CALCULATION FOR HEADER ONLY .....
0367    214  RZTMP=(EBD*RZTTX)+RZSYX
0368         IF (RZTMP.GT.0.0) RTMSO=1000.0/RZTMP
0370         IF (JXFG.LT.3) GO TO 216
0372         RZSYS=RZTMP
0373    216  CONTINUE
0374         IMN=1
0375         IF (RPSZ.GT.RZER) IMN=2
0377    217  CONTINUE
0378         IF ((III.EQ.0).OR.(IMM.EQ.0)) GO TO 220
0380         T=III*RINC
0381         S=T
0382         IF (JS.EQ.0) GO TO 395
0384         GO TO (218,219),ISFG
0385    218  S=JS*RINC
0386         GO TO 395
0387    219  IF (RTSF.GT.0.0) S=SLM/RTSF
0389         GO TO 395
        C
        C##########################################################################
        C
        C                    PRINT HEADER
        C
        C##########################################################################
0390    220  WRITE (ILP,221) (IBUF(IB),IB=1,72)
0391    221  FORMAT (T2,72A1,/,T2,8('---------'))
```

```
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0392          QC=RWD*EPG*EBD
0393          RSS=(QC*RMSZ)/8192.
0394          IFLG=1
0395          IF (RSS.LT.1000.0) GO TO 16
0397          IFLG=2
0398          RSS=RSS/1000.0
0399    16    CONTINUE
0400          KMM=KM(IFLG)
0401          BPG=EPG*EBD
0402          WRITE (ILP,13) LMFLGS(JXFG),LQ(IQFG),RSS,KMM,RWD,RE,EPG,EBD,
             * RWD*BPG,RE*BPG,RMSZ,RCSZ,RZTTX*R,RZSYX*R,RTSED,RTMSO
0403    13    FORMAT (T2,A4,'/',A2,T20,
             C 'ECC PROBABILITY PROGRAM "INTEL-MPD/MC."',
             C //,T2,'MEMORY SYS:  SIZE->  ',F6.1,A2,T36,'WORD WIDTH-> ',F4.0,
             C '+',F3.0,T58,'NO. PAGES-> ',F4.0,'X',F4.0,/,T2,'COMPONENT',
             C ': TOTAL->',F7.0,'+',F7.0,T38,'RAM SIZE-> ',F8.0,T58,
             C 'COL SIZE-> ',F4.0,/,T2,'SYSTEM DATA:',2X,'TTL RATE -> ',
             C F8.5,'%/1K-HRS,',2X,'SYSTEM RATE -> ',F8.5,'%/1K-HRS',
             C //,T2,'FAILURE DATA:',T17,'MTBF NECC ->',F11.2,'HRS,',T45,
             C 'MTBF SYS -> ',F11.2,'HRS')
0404          WRITE (ILP,224) RPSZ,RZD*R,SLM,RZDD*R,RTM,RAVE
0405   224    FORMAT (T2,'HARD ERRORS:',T19,'PARTIAL ->',F6.0,'CELLS/PG',
             C T45,'RATE -> ',F10.6,'% / 1000 HRS',/,T2,'SOFT ERRORS:',T16,
             C '"*"',T20,'MAINT  -> ',F10.0,'HRS,',T45,'RATE -> ',F10.6,
             C '% / 1000 HRS',/,T2,'ANALYSIS DATA:',T20,'PERIOD -> ',F10.2,
             C 'HRS,',T45,'AVE CELL FAILURE ->',F8.1)
0406          K=100
0407          WRITE (ILP,11)
0408    11    FORMAT (T2,'FAILURE TYPE RATIOS:   ',5('----------'),/,T2,
             C '=TYPE=',T14,'=DISTRIBUTION=GEOMETRY=UNIT.RATE/1K HRS=',
             C 'AVE.CELLS=ECC.DISTR=EXPS=')
0409          WRITE (ILP,12) RXZ*R,RMSZ,RZZ*R,AZ,BZ,RHRD*R,BHRD,RXS*R,
             C RMSZ,RZS*R,AS,BS,ECS,RXF*R,RFSZ,RZF*R,AF,BF,ECF
0410    12    FORMAT (T3,'SOFT ERROR  ->[',F7.3,'%]/',F7.0,' = ',E12.5,'%,',
             C F11.3,2X,'[',F6.2,'%]',/,T3,'HARD ERRORS ->[',F7.3,'%]',
             C T65,'[',F6.2,'%]',/,
             C T3,'SINGLE CELL ->',F8.4,'% /',F7.0,' = ',E12.5,'%,'F11.3,2X,
             C F6.2,'%',2X,F4.0,/,T3,'ROW OR COL  ->',F8.4,'% /',F7.0,' = ',
             C E12.5,'%,',F11.3,2X,F6.2,'%',2X,F4.0)
0411          WRITE (ILP,17) RXE*R,RESZ,RZE*R,AE,BE,ECE,RXH*R,RHSZ,RZH*R,
             C AH,BH,ECH,RXT*R,RTSZ,RZT*R,AT,BT,ECT
0412    17    FORMAT (T3,'COLUMN/ROW  ->',F8.4,'% /',F7.0,' = ',
             C E12.5,'%,',F11.3,2X,F6.2,'%',2X,F4.0,/,T3,'HALF CHIP    ->',
             C F8.4,'% /',F7.0,' = ',E12.5,'%,'F11.3,2X,F6.2,'%',2X,F4.0,/,
             C T3,'TOTAL CHIP  ->',F8.4,'% /',F7.0,' = ',E12.5,'%,',
             C F11.3,2X,F6.2,'%',2X,F4.0,/)
0413          IF (IMM.NE.0) GO TO 390
0415          WRITE (ILP,380)
0416   380    FORMAT (1H1,T2,8('---------'))
0417          GO TO 100
0418   390    CONTINUE
        C
        C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
        C
```

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      C                    EQUATION LOOP
      C
      C
            WRITE (ILP,14) LPTR(IMM+10),LH(IMFLG)
       14   FORMAT (T2,'PERIOD',T11,'PM@T:',T24,'R[T].',A4,T44,'MTTF',
           C T52,'ENHANCEMENT',T65,'% - R(T)',/,T2,'-----',T8,
           C '<',A2,' HRS>',T23,'=FUNCTION=',T42,'<  HRS >',T52,
           C '. FACTOR  .',T65,'.    @T  .')
            I=0
      395   TSFT=S
            THRD=T
      400   CONTINUE
            JG=1
            RENH=RZER
      C
      C##########################################################################
      C
      C              RELIABILITY EQUATIONS
      C
      C
            CALL TEST (IMM)
      C
      C##########################################################################
      C
      C                    OUTPUT DATA
      C
      C##########################################################################
      500   CONTINUE
            IF (III.EQ.0) GO TO 510
            WRITE (ITOUT,502) LPTR(IMM+10),I,T*RTSF,RTPG
      502   FORMAT (T2,'** ',A4,5X,'I => ',I4,5X,'T => ',F10.2,10X,
           C 'R => ',F10.7)
            GO TO 100
      510   IZFLG=0
            RTIM=T*RTSF
            RTMX=RTIM
            IF (IMFLG.EQ.2) RTMX=RTIM/RMIL
            IF (I.EQ.0) GO TO 522
            RINT=((ROLD+RTPG)/2.0)*RTM
            IF (ISFLG.EQ.2) RINT=RZER
            RMTTF=RMTTF+RINT
            IF (1.0-RTPG.LE.SZER) GO TO 517
            RMNT=RMTTF/(1.0-RTPG)
            GO TO 520
      517   IZFLG=2
      520   ROLD=RTPG
      522   CONTINUE
            IF ((RTPG.LE.RCNF).AND.(LG.EQ.1)) JG=2
            KLI=KL(IXFG)
            IFLG=0
            IF (((I/ISW)*ISW.NE.I).OR.(I.LT.ILLM)) IFLG=1
            IF (I.GT.IULM) IFLG=1
            IF (I.EQ.IUCD) IFLG=0
            RI=I
```

```
      C      IF (I.EQ.0) GO TO 525
      C      IF (RTPG.LE.0.0) GO TO 525
      C      RZREV=(DLOG(1.0/RTPG))/T
      C      RZTOL=((RZTOL*(RI-1.0))+RZREV)/RI
0463    525  CONTINUE
0464         IF ((I.NE.0).AND.(IFLG.EQ.1)) GO TO 550
0466         L1=LL(JG)
0467         L2=LR(JG)
0468         RCFD=RTPG*100.00
0469         IF (RTSED.GE.1.0) RENH=RMNT/RTSED
0471         IF ((ISFLG+JSFLG.EQ.3).AND.(ILFG.EQ.1)) GO TO 535
0473         GO TO (531,532),IMFLG
0474    531  WRITE (ILP,505) I,RTMX,KLI,RTPG,RMNT,RENH,L1,RCFD,L2
0475    505  FORMAT (T2,I4,T7,F8.0,A2,T24,F8.5,T40,F10.0,T52,F8.0,
            C T65,A1,F5.1,'%',A1)
0476         GO TO 535
0477    532  WRITE (ILP,506) I,RTMX,KLI,RTPG,RMNT,RENH,L1,RCFD,L2
0478    506  FORMAT (T2,I4,T7,F8.2,A2,F8.5,T40,F10.0,T52,F8.0,
            C T65,A1,F5.1,'%',A1)
0479    535  CONTINUE
0480         IF (JG.EQ.2) LG=2
0482    550  CONTINUE
      C
      C###########################################################################
      C
      C                      CALCULATE NEXT 'T' INTERVAL
      C
      C###########################################################################
      C
0483         GO TO (560,570),ISFG
0484    560  IXFLG=1
0485         IXFG=1
0486         IF (JSFLG+ISFLG.LT.4) GO TO 562
0488         JSFLG=1
0489         ISFLG=1
0490    562  CONTINUE
0491         GO TO (564,566),JSFLG
0492    564  T=T+RINC
0493         S=S+RINC
0494         I=I+1
0495         GO TO 568
      C                      ..... SCRUB SOFT ERRORS ....
0496    566  S=RZER
0497    568  CONTINUE
0498         TSFT=S
0499         THRD=T
0500         IF ((S.GE.(SLM/RTSF)).AND.(SLM.NE.RZER)) IXFLG=2
0502         IF (JSFLG.EQ.2) ISFLG=2
0504         IF (IXFLG.EQ.2) JSFLG=2
0506         IF ((LG.EQ.2).AND.(ISFLG.EQ.1)) JSFLG=1
0508         IXFG=ISFLG
0509         GO TO 580
0510    570  CONTINUE
      C          .... SPECIAL MODE AVERAGE SOFT ERROR RATE
```

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0511          IXFG=3
0512          T=T+RINC
0513          I=I+1
0514          GO TO (574,576),IXFLG
0515     574  S=S+RINC
0516          GO TO 578
0517     576  S=RZER
0518          IXFLG=1
0519     578  CONTINUE
0520          THRD=T
0521          TSFT=S
0522          IF (SLM.EQ.RZER) GO TO 580
0524          TSFT=R1+(SLM/1000.)
0525          IF (S.GE.(SLM/RTSF)) IXFLG=2
0527          IF (IXFLG.EQ.2) IXFG=4
0529     580  CONTINUE
        C
        C              .... END EQUATION LOOP ....
        C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
        C
0530          IFLG=0
0531          GO TO (585,590),IDFLG
0532     585  CONTINUE
        C                          .... ITERATE TILL LIST COUNT ....
0533          IFLG=1
0534          IF ((I.GT.IULM).OR.(RTPG.LE.RALMT)) GO TO 650
0536          GO TO 400
0537     590  CONTINUE
        C                          .... ITERATE TILL R(T) BELOW LIMIT ....
0538          IF ((LG.EQ.1).OR.(ILFLG.EQ.2)) GO TO 660
        C              ....  ACCELERATE FAILURE RATE ....
0540          RINC=RINC*IDBK
0541          ILFLG=2
0542     660  CONTINUE
0543          IFLG=2
0544          IF (RTPG.LE.RALMT) GO TO 650
0546          IFLG=3
0547          IF (I.LT.IULM*ICST) GO TO 400
0549          WRITE (ILP,595)
0550     595  FORMAT (T2,'****')
0551     600  CONTINUE
0552     650  CONTINUE
        C
0553          RENH=0.0
0554          IF (RTPG.GT.RALMT) WRITE (ILP,595)
0556          IF (RTSED.GT.1.0) RENH=RMTTF/RTSED
        C
        C################################################################################
        C
        C           THIS IS IT .....    SYSTEM MTBF
        C
        C###############################################################################
0558          WRITE (ILP,675) I,RTMX,RTPG,RMTTF,RENH
0559     675  FORMAT (T38,'=MEMORY MTBF=',4X,'=EF=',/,T2,I4,T7,F10.2,
```

```
FORTRAN IV      V02.04

            C T24,F8.5,T40,F12.2,T52,,F8.0,/,T2,8('---------'),/)
      C
0560          RZTOL=1000./RMTTF
0561          GO TO (676,677,678),JXFG
0562    676   RZTMP=RZTOL+RZSYS
0563          RTSYS=1000.0/RZTMP
0564          GO TO 679
0565    677   RZTMP=RZTOL+RZSYX+(EBD*RZTTX)
0566          RTSYS=1000.0/RZTMP
0567          GO TO 679
0568    678   RTSYS=RMTTF
0569          RZTMP=0.0
0570    679   CONTINUE
0571          IF (RTSED.GT.0.0) RENH=RTSYS/RTSED
0573          WRITE (ILP,680) IFLG,RTSYS,RENH,RZTMP
0574    680   FORMAT (T2,'FIN',1X,I3,T24,'=SYSTEM MTBF=',T40,F12.2,T52,F8.0,
            C T65,E12.5,/,1H1)
0575          GO TO 100
0576          END

FORTRAN IV      V02.1-1

0001          REAL FUNCTION DRTI*8(RZX,RTM,EL,RT)
0002          IMPLICIT REAL*8 (R)
0003          DATA R1/1.0D0/
      C#######################################################################
      C
      C          RS(T) FUNCTION
      C
      C########################################################################
0004          DRTI=(R1/DEXP(RZX*RT))*(RTM**EL)
0005          RETURN
0006          END

FORTRAN IV      V02.1-1

0001          REAL FUNCTION DRTO*8(RZX,RXI,RXO,RN,EL,RT)
0002          IMPLICIT REAL*8 (R)
0003          DATA R1/1.0D0/
      C#######################################################################
      C
      C          BINOMIAL EQUATION FUNCTION
      C
      C########################################################################
0004          EN=RN
0005          EN1=RN-R1
0006          RR=R1/DEXP(RZX*RT)
0007          RXN=RR**EN
0008          RQX=R1-RR
0009          RTRM1=RXN*(RXO**EL)
0010          RTRM2=RN*RQX*(RXI**EN1)
0011          DRTO=RTRM1+RTRM2
0012          RETURN
0013          END
```

```
FORTRAN IV        V02.1-1

      REAL FUNCTION DRTX*8(RZX,RXI,R10,R20,RN,EL,RT)
      IMPLICIT REAL*8 (R)
      DATA R1/1.0D0/,R2/2.0D0/
C################################################################################
C
C     BINOMIAL EQUATION FUNCTION FOR DOUBLE BIT CORRECTION
C
C################################################################################
      EN=RN
      RN1=RN-R1
      EN1=RN1
      RN2=RN-R2
      EN2=RN2
      E2=R2
      RR=R1/DEXP(RZX*RT)
      RXN=RR**EN
      RQX=R1-RR
      RTRM1=RXN*(R20**EL)
      RTRM2=RN*RQX*(RR**EN1)*(R10**EL)
      RTRM3=(RN*RN1*(RQX**E2)*(RXI**EN2))*0.50
      DRTX=RTRM1+RTRM2+RTRM3
      RETURN
      END
```

```
FORTRAN IV      V02.1-1

0001          SUBROUTINE TEST(IMM)
      C
      C##########################################################################
      C
      C       EQUATIONS FOR:
      C                   NON ERROR CORRECTED SYSTEM
      C                   SINGLE BIT CORRECTED SYSTEM
      C                   DOUBLE BIT CORRECTED SYSTEM
      C                   USE OF PARTIALS IN A SYSTEM
      C
      C##########################################################################
0002          IMPLICIT REAL*8 (D,R,S,T,Z)
      C
0003          COMMON /ECC1/RXZ,RXS,RXR,RXC,RXF,RXE,RXH,RXT,RCNF,SZER,SXX
0004          COMMON /ECC2/RMSZ,RCSZ,RWD,BPG,RZD,RZDD,REC,RZER,R1,RTM,RTSF
0005          COMMON /ECC3/IM,ILLM,IULM,RSQ,JSFLG,EPGX,ISFLG,ST,R,RTH,R2
0006          COMMON /ECC4/ISW,RFF,IPM,RTTF,RZTTL,ICST,RALMT,IDBK,IQFG,IUCD
0007          COMMON /ECC5/ISFG,REC1,REC2,IEFLG,RZSYS,ILIM,IDFLG,RAVE
0008          COMMON /ECC6/ITIN,ITOUT,ILP
0009          COMMON /ECC7/RZZ,RZS,RZR,RZC,RZF,RZE,RZH,RZT,RZDX
0010          COMMON /ECC8/ECZ,ECS,ECR,ECC,ECF,ECE,ECH,ECT,ECX
0011          COMMON /ECC9/EW,EW1,EW2,RW,RW1,RW2,S,T,TSFT,THRD
0012          COMMON /ECCA/EPG,EBD,EPSZ,ECA,EPX,EPY,EPZ
0013          COMMON /ECCB/ZT,ZR,ZF,ZE,EZL
0014          COMMON /ECCC/I,IMN,RPRT,RTO,RTPG,RTX,RZDZ,RXX,RSPC1,RSPC2
      C
0015          GO TO (410,420,430),IMM
      C
0016     410  CONTINUE
      C           ######## SINGLE ERROR DETECT EQUATIONS ########
      C
0017          RZO=(1.0/DEXP(RZDD*S))**EW
0018          RXO=(1.0/DEXP(SXX*RZD*THRD))**EW
0019          RYO=(1.0/DEXP(RZTTL*THRD))**EW
      C
0020          RTO=(RZO*RYO*RXO)**EPG
0021          RXO=(1.0/DEXP(RZTTL*THRD))**EBD
0022          RTSYS=(1.0/DEXP(RZSYS*THRD))
0023          RTPG=((RTO*RXO)**EBD)*RTSYS
0024          GO TO 500
      C
0025     420  CONTINUE
      C           ####### SINGLE BIT ERROR CORRECTION EQUATIONS  #####
      C
0026          RZI=DRTI(RZZ,R1,ECZ,TSFT)
0027          RZO=DRTO(RZZ,RZI,R1,RW,ECZ,TSFT)
      C
0028          RSI=DRTI(RZS,RZI,ECS,THRD)
0029          RSO=DRTO(RZS,RSI,RZO,RW,ECS,THRD)
      C
0030          RFI=DRTI(RZF,RSI,ECF,THRD)
0031          RFO=DRTO(RZF,RFI,RSO,RW,ECF,THRD)
      C
0032          REI=DRTI(RZE,RFI,ECE,THRD)
```

```
FORTRAN IV          V02.1-1

0033              REO=DRTO(RZE,REI,RFO,RW,ECE,THRD)
         C
0034              RHI=DRTI(RZH,REI,ECH,THRD)
0035              RHO=DRTO(RZH,RHI,REO,RW,ECH,THRD)
         C
0036              RTI=DRTI(RZT,RHI,ECT,THRD)
0037              RTO=DRTO(RZT,RTI,RHO,RW,ECT,THRD)
         C
0038              RXI=DRTI(RZTTL,RTO,EPG,THRD)
0039              RXO=DRTO(RZTTL,RXI,RTO,RW,EPG,THRD)
         C
0040              RTSYS=1.0/DEXP(RZSYS*THRD)
         C
0041              GO TO (425,422,422),IQFG
         C              .... SPECIAL EQUATION FOR 2-D EFFECTS ....
0042       422    RQR=1.0-(1.0/DEXP(RXR*RZD*THRD*EW))
0043              RQC=1.0-(1.0/DEXP(RXC*RZD*THRD*EW))
0044              RQF=1.0-(1.0/DEXP(RXF*RZD*THRD*EW))
0045              RQE=1.0-(1.0/DEXP(RXE*RZD*THRD*EW))
0046              GO TO (425,424,423),IQFG
0047       423    RSPC1=((1.0-(RQR*RQC))*(1.0-(RQF*RQE)))**EPG
0048              GO TO 425
0049       424    SQX=RQR
0050              IF (RQC.LT.RQR) SQX=RQC
0052              SQZ=RQF
0053              IF (RQE.LT.RQF) SQZ=RQE
0055              RSPC1=((1.0-SQX)*(1.0-SQZ))**EPG
         C
0056       425    RTPG=((RXO*RSPC1)**EBD)*RTSYS
         C
0057              GO TO (500,428),IMN
         C              .... EQUATIONS FOR USE OF PARTIALS ....
0058       428    RPRTO=(1.0/DEXP(RW1*RZDX*THRD))**EPY
0059              RTPX=(RXO*RSPC1)**EPX
         C
0060              RTPG=((RTPX*RPRTO)**EBD)*RTSYS
0061              GO TO 500
         C
0062       430    CONTINUE
         C          ####### DOUBLE BIT ERROR CORRECTION EQUATIONS    ######
         C
0063              RZI=DRTI(RZZ,R1,ECZ,TSFT)
0064              RZO=DRTO(RZZ,RZI,R1,RW1,ECZ,TSFT)
0065              RZX=DRTX(RZZ,RZI,R1,R1,ECZ,TSFT)
         C
0066              RSI=DRTI(RZS,RZI,ECS,THRD)
0067              RSO=DRTO(RZS,RSI,RZO,RW1,ECS,THRD)
0068              RSX=DRTX(RZS,RSI,RZO,RZX,RW,ECS,THRD)
         C
0069              RFI=DRTI(RZF,RSI,ECF,THRD)
0070              RFO=DRTO(RZF,RFI,RSO,RW1,ECF,THRD)
0071              RFX=DRTX(RZF,RFI,RSO,RSX,RW,ECF,THRD)
         C
0072              REI=DRTI(RZE,RFI,ECE,THRD)
```

```
FORTRAN IV      V02.1-1

0073          REO=DRTO(RZE,REI,RFO,RW1,ECE,THRD)
0074          REX=DRTX(RZE,REI,RFO,RFX,RW,ECE,THRD)
       C
0075          RHI=DRTI(RZH,REI,ECH,THRD)
0076          RHO=DRTO(RZH,RHI,REO,RW1,ECH,THRD)
0077          RHX=DRTX(RZH,RHI,REO,REX,RW,ECH,THRD)
       C
0078          RTI=DRTI(RZT,RHI,ECT,THRD)
0079          RTO=DRTO(RZT,RTI,RHO,RW1,ECT,THRD)
0080          RTX=DRTX(RZT,RTI,RHO,RHX,RW,ECT,THRD)
       C
0081          RXI=DRTI(RZTTL,RTI,EPG,THRD)
0082          RXO=DRTO(RZTTL,RXI,RTO,RW1,EPG,THRD)
0083          RXX=DRTX(RZTTL,RXI,RTO,RTX,RW,EPG,THRD)
       C
0084          RTSYS=R1/DEXP(RZSYS*THRD)
       C
0085          GO TO (434,431,431),IQFG
       C            .... SPECIAL EQUATION FOR 2-D EFFECTS ....
0086     431  RTP=DRTI(RZR,R1,R1,THRD)
0087          RQR=1.0-DRTO(RZR,RTP,R1,RW1,R1,THRD)
0088          RTP=DRTI(RZC,R1,R1,THRD)
0089          RQC=1.0-DRTO(RZC,RTP,R1,RW1,R1,THRD)
0090          RTP=DRTI(RZF,R1,R1,THRD)
0091          RQF=1.0-DRTO(RZF,RTP,R1,RW1,R1,THRD)
0092          RTP=DRTI(RZE,R1,R1,THRD)
0093          RQE=1.0-DRTO(RZE,RTP,R1,RW1,R1,THRD)
0094          GO TO (434,433,432),IQFG
0095     432  RSPC2=((1.0-(RQR*RQC))*(1.0-(RQF*RQE)))**EPG
0096          GO TO 434
0097     433  SQX=RQR
0098          IF (RQC.LT.RQR) SQX=RQC
0100          SQZ=RQF
0101          IF (RQE.LT.RQF) SQZ=RQE
0103          RSPC2=((1.0-SQX)*(1.0-SQZ))**EPG
       C
0104     434  RTPG=((RXX*RSPC2)**EBD)*RTSYS
0105          GO TO (500,435),IMN
       C            .... EQUATIONS FOR USE OF PARTIALS ....
0106     435  CONTINUE
0107          GO TO (439,436,436),IQFG
0108     436  RQR=1.0-(1.0/DEXP(RXR*RZD*THRD*EW))
0109          RQC=1.0-(1.0/DEXP(RXC*RZD*THRD*EW))
0110          RQF=1.0-(1.0/DEXP(RXF*RZD*THRD*EW))
0111          RQE=1.0-(1.0/DEXP(RXE*RZD*THRD*EW))
0112          GO TO (439,438,437),IQFG
0113     437  RSPC1=((1.0-(RQR*RQC))*(1.0-(RQF*RQE)))**EPG
0114          GO TO 439
0115     438  RSPC1=((1.0-SQX)*(1.0-SQZ))**EPG
0116     439  RPRT0=(1.0/DEXP(RW2*RZDX*THRD))**EPZ
0117          RPRT1=(RTO*RSPC1)**EPY
0118          RPRT2=(RTX*RSPC2)**EPX
       C
0119          RTPG=((RPRT0*RPRT1*RPRT2)**EBD)*RTSYS
```

```
FORTRAN IV        V02.1-1

0120         GO TO 500
     C
0121     440 CONTINUE
     C       FUTURE TESTS HERE
0122     500 CONTINUE
0123         RETURN
0124         END
FORTRAN IV        V02.1-1

0001         SUBROUTINE HELP
0002         COMMON /ECC6/ITIN,ITOUT,ILP
0003         WRITE (ITOUT,20)
0004      20 FORMAT (/,T10,2('********'),2X,'HELP TEXT  ',2('********'),//
            C ,T2,'.PRAMETER...RANGE...............COMMENTS.....',/,
            C T15,'NECC - NON ECC EVALUATION RUN.',/,T15,'SECC - SINGLE',
            C ' BIT ERROR CORRECTION RUN.',/,T15,'DECC - DOUBLE BIT ERROR'
            C ' ERROR CORRECTION RUN.')
0005         WRITE (ITOUT,25)
0006      25 FORMAT (T2,'INDEX:',T12,4('........'),T50,'<DATA TYPE INTEGER>'
            C ,/,T18,'0 - SPECIFIES FULL-OUTPUT NORMAL RUN.',/,T17,'>0 -',
            C ' SPECIFIES SINGLE POINT CALCULATION OF R-FUNCTION @ T',/,
            C T22,'WHERE T = INDEX * TIME,   PURPOSE IS TO ASSIST USER',/,
            C T22,'DETERMINE BEST TIME INTERVAL FOR RUNS.')
0007         WRITE (ITOUT,30)
0008      30 FORMAT (T2,'TIME:',T12,4('........'),T50,'<DATA TYPE FLOATING',
            C ' PT.>',/,T16,'>0. - SPECIFIES INTERVAL OF TIME BETWEEN RUN-',
            C 'TIME',/,T22,'EVALUATION POINTS')
0009         WRITE (ITOUT,35)
0010      35 FORMAT (T2,'PAGE:',T12,4('........'),T50,'<DATA TYPE INTEGER>',
            C /,T17,'>1 - NUMBER OF MEMORY ROWS PER BOARD.',/,
            C T2,'BOARDS:',T12,4('........'),T50,'<DATA TYPE INTEGER>',/,
            C T17,'>1 - NUMBER OF BOARDS PER MEMORY SYSTEM.',/)
0011         WRITE (ITOUT,40)
0012      40 FORMAT (T20,' ** HIT <RETURN> TO CONTINUE **')
0013         READ (ITIN,45) IDUM
0014      45 FORMAT (A2)
0015         WRITE (ITOUT,50)
0016      50 FORMAT (//,T20,' # ADDITIONAL POINTER PARAMETERS #',//,
            C T2,'POINTER:',T12,4('........'),T50,'<DATA TYPE LITERAL>',/,
            C T15,'LIST  -  LIST OUTPUT PARAMETERS.',/,
            C T15,'SIZE  -  MEMORY COMPONENT & SYSTEM PARAMETERS.',/,
            C T15,'RATE  -  COMPONENT & SYSTEM FAILURE RATES.',/,
            C T15,'DIST  -  COMPONENT FAILURE-TYPE DISTRIBUTION.',/,
            C T15,'COMM  -  OUTPUT RUN-TIME COMMENT LINE')
0017         WRITE (ITOUT,55)
0018      55 FORMAT (T15,'ABORT -  EXIT PROGRAM.',/,
            C T15,'DUMP  -  DISPLAY  < LIST, SIZE, RATE, DIST, COMM >',/,
            C T15,'PURGE -  PRINT REST OF RUN-TIME OUTPUT BUFFER',//,
            C T15,'FLAG  -  USE OF TTL & SYSTEM FAILURE RATES,   Q-FLAG',/,
            C T22,'SYS = TTL @ BOARD LEVEL, SYSTEM USED WITH MEMORY',/,
            C T22,'MPD = TTL N.U., SYSTEM RATE LISTED IN HEADER ONLY',/,
            C T28,'SOFT ERROR RATE SPECIAL MPD ALGORITHM - MEM CYCLES',/,
            C T22,'MSO = (TTL X BOARDS) + SYSTEM COMBINED WITH MEMORY',/,
            C T22,'Q1  =  ONE DIMENSIONAL ARRAY MODEL',/,
            C T22,'Q2  =  SAME AS Q1, PLUS SPECIAL TWO DIMENSIONAL FIX',/,
            C T10,5('********'),///)
0019         RETURN
0020         END
     C       END OF PROGRAM
```

```
--------------------------------------------------------------------------------------------

SYS /Q1              ECC PROBABILITY PROGRAM "INTEL-MPD/MC. "

MEMORY SYS: SIZE->    32. 0KB      WORD WIDTH->  16. + 6.  NO. PAGES->    1. X   1.
COMPONENT: TOTAL->    16. +     6.   RAM SIZE->    16384.  COL SIZE-> 128.
SYSTEM DATA:   TTL RATE ->  0. 00000%/1K-HRS,   SYSTEM RATE ->  0. 00000%/1K-HRS

FAILURE DATA:   MTBF. NECC ->    49212. 60HRS,  MTBF. SYS ->            0. 00HRS
HARD ERRORS:        PARTIAL ->    0. CELLS/PG   RATE ->    0. 027000% / 1000 HRS
SOFT ERRORS:    "*" MAINT   ->         0. HRS,  RATE ->    0. 100000% / 1000 HRS
ANALYSIS DATA:      PERIOD ->  100000. 00HRS,  AVE CELL FAILURE ->     16. 2
FAILURE TYPE RATIOS:  ---------------------------------------------------------
=TYPE=       =DISTRIBUTION=GEOMETRY=UNIT. RATE/1K HRS=AVE. CELLS=ECC. DISTR=EXPS=
 SOFT ERROR   ->[ 78. 740%]/ 16384.  =   0. 61035E-05%,        0. 787   [   4. 87%]
 HARD ERRORS  ->[ 21. 260%]                                             [  95. 13%]
 SINGLE CELL  -> 50. 0000% / 16384.  =   0. 82397E-06%,        0. 106     0. 69%     1.
 ROW OR COL   -> 43. 7000% /    128.  =   0. 92180E-04%,       11. 892    77. 36%   128.
 COLUMN/ROW   ->  6. 2000% /     64.  =   0. 26156E-04%,        3. 374    21. 95%     2.
 HALF CHIP    ->  0. 0000% /      2.  =   0. 00000E+00%,        0. 000     0. 00%    32.
 TOTAL CHIP   ->  0. 0000% /      1.  =   0. 00000E+00%,        0. 000     0. 00%     2.

PERIOD   PM@T:           R[T]. SECC               MTTF     ENHANCEMENT   % - R(T)
----- <M- HRS>          =FUNCTION=              <  HRS >      FACTOR         @T
   0      0. 00    1. 00000                            0.          0.        100. 0%
   1      0. 10    0. 99332                     14922026.        303.         99. 3%
   2      0. 20    0. 97389                      7584078.        154.         97. 4%
   3      0. 30    0. 94293                      5149121.        105.         94. 3%
   4      0. 40    0. 90200                      3939900.         80.         90. 2%
   5      0. 50    0. 85289                      3221005.         65.         85. 3%
   6      0. 60    0. 79748                      2747323.         56.         79. 7%
   7      0. 70    0. 73770                      2413825.         49.         73. 8%
   8      0. 80    0. 67537                      2168007.         44.         67. 5%
   9      0. 90    0. 61217                      1980705.         40.         61. 2%
  10      1. 00    0. 54958                      1834422.         37.         55. 0%
  11      1. 10    0. 48884                      1718017.         35.         48. 9%
  12      1. 20    0. 43095                      1624061.         33.         43. 1%
  13      1. 30    0. 37666                      1547397.         31.         37. 7%
  14      1. 40    0. 32650                      1484334.         30.       < 32. 6%>
  15      1. 50    0. 28075                      1432149.         29.         28. 1%
  16      1. 60    0. 23956                      1388787.         28.         24. 0%
  17      1. 70    0. 20290                      1352665.         27.         20. 3%
  18      1. 80    0. 17062                      1322533.         27.         17. 1%
  19      1. 90    0. 14248                      1297395.         26.         14. 2%
  20      2. 00    0. 11819                      1276437.         26.         11. 8%
  21      2. 10    0. 09741                      1258993.         26.          9. 7%
  22      2. 20    0. 07979                      1244505.         25.          8. 0%
  23      2. 30    0. 06496                      1232508.         25.          6. 5%
  24      2. 40    0. 05258                      1222606.         25.          5. 3%
  25      2. 50    0. 04232                      1214463.         25.          4. 2%
  26      2. 60    0. 03388                      1207796.         25.          3. 4%
  27      2. 70    0. 02698                      1202358.         24.          2. 7%
  28      2. 80    0. 02137                      1197945.         24.          2. 1%
  29      2. 90    0. 01685                      1194379.         24.          1. 7%
  30      3. 00    0. 01322                      1191512.         24.          1. 3%
 ****
                                             =MEMORY MTBF=      =EF=
  31        3. 00          0. 01322              1175755. 35      24.
-------------------------------------------------------------------------------

 FIN    1                 =SYSTEM MTBF=          1175755. 35      24.         0. 85052E-03
```

```
SYS /Q1                    ECC PROBABILITY PROGRAM "INTEL-MPD/MC."

MEMORY SYS:  SIZE->      4.1MB       WORD WIDTH->  16.+ 6.  NO.PAGES->    1.X128.
COMPONENT:  TOTAL->  2048.+    768.    RAM SIZE->   16384.  COL SIZE-> 128.
SYSTEM DATA:   TTL RATE ->  0.00000%/1K-HRS,   SYSTEM RATE ->  0.00000%/1K-HRS

FAILURE DATA:   MTBF.NECC ->       384.47HRS,  MTBF.SYS ->          0.00HRS
HARD ERRORS:        PARTIAL ->     0.CELLS/PG   RATE ->    0.027000% / 1000 HRS
SOFT ERRORS:   "*" MAINT   ->          0.HRS,  RATE ->    0.100000% / 1000 HRS
ANALYSIS DATA:      PERIOD ->     8000.00HRS,  AVE CELL FAILURE ->     16.2
FAILURE TYPE RATIOS:  ----------------------------------------------------------
=TYPE=        =DISTRIBUTION=GEOMETRY=UNIT.RATE/1K HRS=AVE.CELLS=ECC.DISTR=EXPS=
 SOFT ERROR   ->[ 78.740%]/ 16384.  =   0.61035E-05%,       0.787   [  4.87%]
 HARD ERRORS  ->[ 21.260%]                                          [ 95.13%]
 SINGLE CELL  -> 50.0000% / 16384.  =   0.82397E-06%,       0.106     0.69%     1.
 ROW OR COL   -> 43.7000% /    128.  =   0.92180E-04%,      11.892    77.36%   128.
 COLUMN/ROW   ->  6.2000% /     64.  =   0.26156E-04%,       3.374    21.95%     2.
 HALF CHIP    ->  0.0000% /      2.  =   0.00000E+00%,       0.000     0.00%    32.
 TOTAL CHIP   ->  0.0000% /      1.  =   0.00000E+00%,       0.000     0.00%     2.

PERIOD    PM@T:              R[T].SECC              MTTF     ENHANCEMENT   % - R(T)
----- < - HRS>             =FUNCTION=            <  HRS >      FACTOR         @T
   0        0.               1.00000                  0.          0.        100.0%
   1      8000.              0.99446            1439611.       3744.         99.4%
   2     16000.              0.97804             722580.       1879.         97.8%
   3     24000.              0.95132             484470.       1260.         95.1%
   4     32000.              0.91518             366101.        952.         91.5%
   5     40000.              0.87080             295638.        769.         87.1%
   6     48000.              0.81955             249140.        648.         82.0%
   7     56000.              0.76294             216349.        563.         76.3%
   8     64000.              0.70256             192135.        500.         70.3%
   9     72000.              0.63998             173652.        452.         64.0%
  10     80000.              0.57670             159190.        414.         57.7%
  11     88000.              0.51411             147663.        384.         51.4%
  12     96000.              0.45341             138346.        360.         45.3%
  13    104000.              0.39562             130737.        340.         39.6%
  14    112000.              0.34153             124475.        324.       < 34.2%>
  15    120000.              0.29171             119297.        310.         29.2%
  16    128000.              0.24653             115001.        299.         24.7%
  17    136000.              0.20616             111433.        290.         20.6%
  18    144000.              0.17059             108471.        282.         17.1%
  19    152000.              0.13968             106017.        276.         14.0%
  20    160000.              0.11318             103990.        270.         11.3%
  21    168000.              0.09076             102322.        266.          9.1%
  22    176000.              0.07202             100958.        263.          7.2%
  23    184000.              0.05656              99849.        260.          5.7%
  24    192000.              0.04397              98954.        257.          4.4%
  25    200000.              0.03382              98237.        256.          3.4%
  26    208000.              0.02575              97668.        254.          2.6%
  27    216000.              0.01941              97220.        253.          1.9%
  28    224000.              0.01448              96872.        252.          1.4%
  29    232000.              0.01069              96603.        251.          1.1%
  30    240000.              0.00782              96397.        251.          0.8%
                                           =MEMORY MTBF=      =EF=
  31    240000.00            0.00782              95643.55     249.
---------------------------------------------------------------------------

FIN    1                =SYSTEM MTBF=          95643.55     249.         0.10455E-01
```

SYS /Q1 ECC PROBABILITY PROGRAM "INTEL-MPD/MC."

MEMORY SYS: SIZE-> 64.0KB WORD WIDTH-> 32. + 7. NO. PAGES-> 1. X 1.
COMPONENT: TOTAL-> 32. + 7. RAM SIZE-> 16384. COL SIZE-> 128.
SYSTEM DATA: TTL RATE -> 0.00000%/1K-HRS, SYSTEM RATE -> 0.00000%/1K-HRS

FAILURE DATA: MTBF.NECC -> 24606.30HRS, MTBF.SYS -> 0.00HRS
HARD ERRORS: PARTIAL -> 0. CELLS/PG RATE -> 0.027000% / 1000 HRS
SOFT ERRORS: "*" MAINT -> 0. HRS, RATE -> 0.100000% / 1000 HRS
ANALYSIS DATA: PERIOD -> 66000.00HRS, AVE CELL FAILURE -> 16.2
FAILURE TYPE RATIOS:

=TYPE=	=DISTRIBUTION=	=GEOMETRY=	=UNIT. RATE/1K HRS=	=AVE. CELLS=	=ECC. DISTR=	=EXPS=
SOFT ERROR	->[78.740%]/	16384.	= 0.61035E-05%,	0.787	[4.87%]	
HARD ERRORS	->[21.260%]				[95.13%]	
SINGLE CELL	-> 50.0000% /	16384.	= 0.82397E-06%,	0.106	0.69%	1.
ROW OR COL	-> 43.7000% /	128.	= 0.92180E-04%,	11.892	77.36%	128.
COLUMN/ROW	-> 6.2000% /	64.	= 0.26156E-04%,	3.374	21.95%	2.
HALF CHIP	-> 0.0000% /	2.	= 0.00000E+00%,	0.000	0.00%	32.
TOTAL CHIP	-> 0.0000% /	1.	= 0.00000E+00%,	0.000.	0.00%	2.

PERIOD -----	PM@T: < - HRS>	R[T]. SECC =FUNCTION=	MTTF < HRS >	ENHANCEMENT FACTOR	% - R(T) @T
0	0.	1.00000	0.	0.	100.0%
1	66000.	0.99070	7066011.	287.	99.1%
2	132000.	0.96388	3604737.	146.	96.4%
3	198000.	0.92173	2458257.	100.	92.2%
4	264000.	0.86699	1890484.	77.	86.7%
5	330000.	0.80276	1554231.	63.	80.3%
6	396000.	0.73219	1333790.	54.	73.2%
7	462000.	0.65828	1179584.	48.	65.8%
8	528000.	0.58374	1066829.	43.	58.4%
9	594000.	0.51088	981755.	40.	51.1%
10	660000.	0.44151	916096.	37.	44.2%
11	726000.	0.37700	864581.	35.	37.7%
12	792000.	0.31821	823686.	33.	< 31.8%>
13	858000.	0.26564	790958.	32.	26.6%
14	924000.	0.21942	764629.	31.	21.9%
15	990000.	0.17941	743388.	30.	17.9%
16	1056000.	0.14528	726238.	30.	14.5%
17	1122000.	0.11655	712400.	29.	11.7%
18	1188000.	0.09267	701259.	28.	9.3%
19	1254000.	0.07305	692319.	28.	7.3%
20	1320000.	0.05712	685174.	28.	5.7%
21	1386000.	0.04431	679492.	28.	4.4%
22	1452000.	0.03411	674998.	27.	3.4%
23	1518000.	0.02607	671465.	27.	2.6%
24	1584000.	0.01979	668705.	27.	2.0%
25	1650000.	0.01492	666562.	27.	1.5%
26	1716000.	0.01118	664910.	27.	1.1%
27	1782000.	0.00832	663644.	27.	0.8%
			=MEMORY MTBF=	=EF=	
28	1782000.00	0.00832	658122.51	27.	

FIN 1 =SYSTEM MTBF= 658122.51 27. 0.15195E-02

SYS /Q1 ECC PROBABILITY PROGRAM "INTEL-MPD/MC."

MEMORY SYS: SIZE-> 8. 2MB WORD WIDTH-> 32. + 7. NO. PAGES-> 1. X128.
COMPONENT: TOTAL-> 4096. + 896. RAM SIZE-> 16384. COL SIZE-> 128.
SYSTEM DATA: TTL RATE -> 0. 00000%/1K-HRS, SYSTEM RATE -> 0. 00000%/1K-HRS

FAILURE DATA: MTBF. NECC -> 192. 24HRS, MTBF. SYS -> 0. 00HRS
HARD ERRORS: PARTIAL -> 0. CELLS/PG RATE -> 0. 027000% / 1000 HRS
SOFT ERRORS: "*" MAINT -> 0. HRS, RATE -> 0. 100000% / 1000 HRS
ANALYSIS DATA: PERIOD -> 5000. 00HRS, AVE CELL FAILURE -> 16. 2
FAILURE TYPE RATIOS: --

=TYPE=	=DISTRIBUTION=	=GEOMETRY=	=UNIT. RATE/1K HRS=	=AVE. CELLS=	=ECC. DISTR=	=EXPS=
SOFT ERROR ->	[78. 740%]/	16384. =	0. 61035E-05%,	0. 787	[4. 87%]	
HARD ERRORS ->	[21. 260%]				[95. 13%]	
SINGLE CELL ->	50. 0000% /	16384. =	0. 82397E-06%,	0. 106	0. 69%	1.
ROW OR COL ->	43. 7000% /	128. =	0. 92180E-04%,	11. 892	77. 36%	128.
COLUMN/ROW ->	6. 2000% /	64. =	0. 26156E-04%,	3. 374	21. 95%	2.
HALF CHIP ->	0. 0000% /	2. =	0. 00000E+00%,	0. 000	0. 00%	32.
TOTAL CHIP ->	0. 0000% /	1. =	0. 00000E+00%,	0. 000	0. 00%	2.

PERIOD -----	PM@T: < - HRS>	R[T]. SECC =FUNCTION=	MTTF < HRS >	ENHANCEMENT FACTOR	% - R(T) @T
0	0.	1. 00000	0.	0.	100. 0%
1	5000.	0. 99306	718156.	3736.	99. 3%
2	10000.	0. 97257	360766.	1877.	97. 3%
3	15000.	0. 93940	242201.	1260.	93. 9%
4	20000.	0. 89494	183350.	954.	89. 5%
5	25000.	0. 84095	148393.	772.	84. 1%
6	30000.	0. 77946	125392.	652.	77. 9%
7	35000.	0. 71269	109232.	568.	71. 3%
8	40000.	0. 64283	97356.	506.	64. 3%
9	45000.	0. 57202	88344.	460.	57. 2%
10	50000.	0. 50219	81346.	423.	50. 2%
11	55000.	0. 43499	75818.	394.	43. 5%
12	60000.	0. 37176	71398.	371.	37. 2%
13	65000.	0. 31351	67835.	353.	< 31. 4%>
14	70000.	0. 26090	64949.	338.	26. 1%
15	75000.	0. 21425	62605.	326.	21. 4%
16	80000.	0. 17364	60702.	316.	17. 4%
17	85000.	0. 13888	59159.	308.	13. 9%
18	90000.	0. 10963	57913.	301.	11. 0%
19	95000.	0. 08542	56913.	296.	8. 5%
20	100000.	0. 06569	56116.	292.	6. 6%
21	105000.	0. 04987	55486.	289.	5. 0%
22	110000.	0. 03737	54992.	286.	3. 7%
23	115000.	0. 02765	54609.	284.	2. 8%
24	120000.	0. 02019	54316.	283.	2. 0%
25	125000.	0. 01456	54093.	281.	1. 5%
26	130000.	0. 01037	53927.	281.	1. 0%
27	135000.	0. 00729	53804.	280.	0. 7%
			=MEMORY MTBF=	=EF=	
28	135000. 00	0. 00729	53412. 22	278.	

FIN 1 =SYSTEM MTBF= 53412. 22 278. 0. 18722E-01

```
SYS /01              ECC PROBABILITY PROGRAM "INTEL-MPD/MC."

MEMORY SYS: SIZE->    128. 0KB       WORD WIDTH->  64. + 8.  NO. PAGES->    1. X   1.
COMPONENT: TOTAL->     64. +      8.    RAM SIZE->   16384.  COL. SIZE-> 128.
SYSTEM DATA:  TTL RATE ->  0. 00000%/1K-HRS,  SYSTEM RATE ->  0. 00000%/1K-HRS

FAILURE DATA:  MTBF. NECC ->   12303. 15HRS, MTBF. SYS ->         0. 00HRS
HARD ERRORS:      PARTIAL ->   0. CELLS/PG  RATE ->   0. 027000% / 1000 HRS
SOFT ERRORS:  "*" MAINT   ->         0. HRS, RATE ->   0. 100000% / 1000 HRS
ANALYSIS DATA:     PERIOD ->   33000. 00HRS, AVE CELL FAILURE ->    16. 2
FAILURE TYPE RATIOS:  ------------------------------------------------------
=TYPE=      =DISTRIBUTION=GEOMETRY=UNIT. RATE/1K HRS=AVE. CELLS=ECC. DISTR=EXPS=
 SOFT ERROR  ->[ 78. 740%]/ 16384.  =  0. 61035E-05%,      0. 787  [  4. 87%]
 HARD ERRORS ->[ 21. 260%]                                        [ 95. 13%]
 SINGLE CELL -> 50. 0000% / 16384.  =  0. 82397E-06%,      0. 106    0. 69%    1.
 ROW OR COL  -> 43. 7000% /   128.  =  0. 92180E-04%,     11. 892   77. 36%  128.
 COLUMN/ROW  ->  6. 2000% /    64.  =  0. 26156E-04%,      3. 374   21. 95%    2.
 HALF CHIP   ->  0. 0000% /     2.  =  0. 00000E+00%,      0. 000    0. 00%   32.
 TOTAL CHIP  ->  0. 0000% /     1.  =  0. 00000E+00%,      0. 000    0. 00%    2.

PERIOD   PM@T:           R[T]. SECC         MTTF     ENHANCEMENT  % - R(T)
----- < - HRS>          =FUNCTION=        <  HRS >     FACTOR        @T
  0        0.             1. 00000              0.        0.      100. 0%
  1    33000.             0. 99197        4092667.      333.       99. 2%
  2    66000.             0. 96871        2084463.      169.       96. 9%
  3    99000.             0. 93192        1418701.      115.       93. 2%
  4   132000.             0. 88376        1088549.       88.       88. 4%
  5   165000.             0. 82663         892655.       73.       82. 7%
  6   198000.             0. 76308         763911.       62.       76. 3%
  7   231000.             0. 69556         673564.       55.       69. 6%
  8   264000.             0. 62639         607238.       49.       62. 6%
  9   297000.             0. 55758         556949.       45.       55. 8%
 10   330000.             0. 49083         517906.       42.       49. 1%
 11   363000.             0. 42747         487054.       40.       42. 7%
 12   396000.             0. 36848         462357.       38.     < 36. 8%>
 13   429000.             0. 31451         442398.       36.       31. 5%
 14   462000.             0. 26592         426159.       35.       26. 6%
 15   495000.             0. 22280         412889.       34.       22. 3%
 16   528000.             0. 18504         402018.       33.       18. 5%
 17   561000.             0. 15240         393104.       32.       15. 2%
 18   594000.             0. 12450         385797.       31.       12. 5%
 19   627000.             0. 10093         379818.       31.       10. 1%
 20   660000.             0. 08120         374936.       30.        8. 1%
 21   693000.             0. 06487         370964.       30.        6. 5%
 22   726000.             0. 05146         367744.       30.        5. 1%
 23   759000.             0. 04056         365147.       30.        4. 1%
 24   792000.             0. 03176         363061.       30.        3. 2%
 25   825000.             0. 02472         361395.       29.        2. 5%
 26   858000.             0. 01912         360071.       29.        1. 9%
 27   891000.             0. 01471         359025.       29.        1. 5%
 28   924000.             0. 01125         358203.       29.        1. 1%
 29   957000.             0. 00856         357561.       29.        0. 9%
                                      =MEMORY MTBF=    =EF=
 30   957000. 00          0. 00856        354499. 33     29.
-----------------------------------------------------------------------

FIN    1             =SYSTEM MTBF=        354499. 33     29.       0. 28209E-02
```

```
SYS /Q1              ECC PROBABILITY PROGRAM "INTEL-MPD/MC."

MEMORY SYS: SIZE->     16.4MB       WORD WIDTH->  64.+ 8.  NO.PAGES->    1.X128.
COMPONENT: TOTAL->  8192.+  1024.    RAM SIZE->    16384.  COL SIZE-> 128.
SYSTEM DATA:   TTL RATE ->  0.00000%/1K-HRS,   SYSTEM RATE ->  0.00000%/1K-HRS

FAILURE DATA:  MTBF.NECC ->        96.12HRS,  MTBF.SYS ->           0.00HRS
HARD ERRORS:       PARTIAL ->     0.CELLS/PG   RATE ->     0.027000% / 1000 HRS
SOFT ERRORS:   "*" MAINT   ->          0.HRS,  RATE ->     0.100000% / 1000 HRS
ANALYSIS DATA:     PERIOD ->     2500.00HRS,  AVE CELL FAILURE ->    16.2
FAILURE TYPE RATIOS:  ---------------------------------------------------------
=TYPE=        =DISTRIBUTION=GEOMETRY=UNIT.RATE/1K HRS=AVE.CELLS=ECC.DISTR=EXPS=
 SOFT ERROR   ->[ 78.740%]/ 16384.  =   0.61035E-05%,        0.787   [   4.87%]
 HARD ERRORS ->[ 21.260%]                                          [  95.13%]
 SINGLE CELL -> 50.0000% / 16384.  =   0.82397E-06%,        0.106     0.69%      1.
 ROW OR COL  -> 43.7000% /    128.  =   0.92180E-04%,       11.892    77.36%   128.
 COLUMN/ROW  ->   6.2000% /     64.  =   0.26156E-04%,        3.374    21.95%     2.
 HALF CHIP   ->   0.0000% /      2.  =   0.00000E+00%,        0.000     0.00%    32.
 TOTAL CHIP  ->   0.0000% /      1.  =   0.00000E+00%,        0.000     0.00%     2.
```

PERIOD -----	PM@T: < - HRS>	R[T].SECC =FUNCTION=	MTTF < HRS >	ENHANCEMENT . FACTOR .	% - R(T) @T
0	.0.M-	1.00000	0.	0.	100.0%
1	2500.	0.99401	416361.	4332.	99.4%
2	5000.	0.97629	209042.	2175.	97.6%
3	7500.	0.94751	140217.	1459.	94.8%
4	10000.	0.90869	106020.	1103.	90.9%
5	12500.	0.86119	85676.	891.	86.1%
6	15000.	0.80658	72264.	752.	80.7%
7	17500.	0.74658	62816.	654.	74.7%
8	20000.	0.68298	55851.	581.	68.3%
9	22500.	0.61752	50543.	526.	61.8%
10	25000.	0.55187	46400.	483.	55.2%
11	27500.	0.48749	43106.	448.	48.7%
12	30000.	0.42566	40453.	421.	42.6%
13	32500.	0.36741	38295.	398.	< 36.7%>
14	35000.	0.31350	36528.	380.	31.3%
15	37500.	0.26445	35074.	365.	26.4%
16	40000.	0.22053	33876.	352.	22.1%
17	42500.	0.18183	32888.	342.	18.2%
18	45000.	0.14822	32075.	334.	14.8%
19	47500.	0.11947	31407.	327.	11.9%
20	50000.	0.09521	30862.	321.	9.5%
21	52500.	0.07503	30419.	316.	7.5%
22	55000.	0.05847	30061.	313.	5.8%
23	57500.	0.04506	29774.	310.	4.5%
24	60000.	0.03434	29546.	307.	3.4%
25	62500.	0.02588	29367.	306.	2.6%
26	65000.	0.01929	29227.	304.	1.9%
27	67500.	0.01422	29120.	303.	1.4%
28	70000.	0.01037	29037.	302.	1.0%
29	72500.	0.00748	28975.	301.	0.7%
			=MEMORY MTBF=	=EF=	
30	72500.00	0.00748	28758.48	299.	

```
FIN   1              =SYSTEM MTBF=          28758.48     299.          0.34772E-01
```